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AN INVESTIGATION OF LATERAL TRACKING TECHNIQUES, FLIGHT DIRECTORS AND AUTOMATIC CONTROL COUPLING ON DECELERATING IFR APPROACHES FOR ROTORCRAFT

by

S. Baillie, S. Kereliuk and R. Hoh

National Aeronautical Establishment

DTIC

OTTAWA
OCTOBER 1988

AERONAUTICAL NOTE
NAE-AN-55
NRC NO. 29604

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AN INVESTIGATION OF LATERAL TRACKING TECHNIQUES, FLIGHT DIRECTORS AND AUTOMATIC CONTROL COUPLING ON DECELERATING IFR APPROACHES FOR ROTORCRAFT

ÉTUDE SUR LES TECHNIQUES DE TENUE D'AXE LATÉRAL, LES DIRECTEURS DE VOL ET LE COUPLAGE DE COMMANDE AUTOMATIQUE POUR LES APPROCHES IFR EN DÉCÉLÉRATION DES GIRAVIONS

by/par

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AERONAUTICAL NOTE
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ABSTRACT

An in-flight simulation experiment was performed to investigate the impact on handling qualities and certification of various issues associated with low minima decelerating flight directed IFR approaches for rotorcraft. These issues were the use of crab versus sideslip techniques to maintain lateral tracking under crosswind conditions, the effects of various methods of vertical axis (glideslope) display, guidance and control, and the benefits of coupling flight director signals directly to the rotorcraft control actuators. The program was performed at the Flight Research Laboratory of the National Aeronautical Establishment (NAE), using the NAE Bell 205 Airborne Simulator and was partially funded by the United States Federal Aviation Administration. Experimental results demonstrated that crab technique approaches were satisfactory for all approach speeds and wind conditions investigated (up to 30-knot crosswinds). A factor not addressed in this study was the visual orientation of the landing pad at breakout to flight with visual references. Sideslipping approaches were also shown to be satisfactory until the steady state lateral acceleration exceeded approximately 0.07 G. While coupling of the collective actuator directly to the flight director provided the best glideslope tracking, evaluations showed that the configuration with a 2-cue (pitch and roll) flight director, using only a raw glideslipe presentation, provided satisfactory handling qualities and was considered by FAA and DOT representatives to be certifiable for IFR flight. Coupling of any single axis of control to the flight director was demonstrated to provide slight workload relief benefits and the collective axis was judged to be the most likely candidate axis for this implementation.

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RÉSUMÉ

On a procédé à une simulation en vol pour étudier l'effet sur la maniabilité et les possibilités d'homologation de divers éléments associés aux approches IFR dirigées en décélération à faibles minima des giravions. Les éléments étudiés étaient l'utilisation de la technique d'approche en crabe par rapport à la technique d'approche en glissement latéral pour la tenue de l'axe latéral par vent de travers, les effets de diverses méthodes d'affichage de l'axe vertical (alignement de descente), de guidage et de contrôle, et les avantages de coupler les signaux du directeur de vol directement aux vérins de commande du giravion. Le programme d'études a été mené au Laboratoire de recherches en vol de l'Établissement national aéronautique (ÉNA), à l'aide du simulateur aéroporté Bell 205 de l'ÉNA et a reçu la participation financière de l'United States Federal Aviation Administration. Les expériences ont démontré que la technique d'approche en crabe donnait des résultats satisfaisants pour toutes les vitesses d'approche et conditions de vent étudiées (vents de travers atteignant 30 noeuds). Un facteur qui n'a pas été étudié est l'orientation visuelle de la plate-forme d'atterrissage au point de passage au vol par références visuelles. Les approches en glissement latéral ont également donné des résultats satisfaisants jusqu'à ce que l'accélération latérale régulière dépasse 0.07 G. Le couplage du vérin de commande de pas collectif directement au directeur de vol a donné les meilleurs résultats de tenue d'axe d'alignement de descente; toutefois, l'évaluation des résultats a démontré qu'une configuration à deux signaux (2-cue) (tangage et roulis) du directeur de vol, ne faisant appel qu'à une présentation sommaire de l'alignement de descente, assurait une maniabilité satisfaisante. En outre, les représentants de la FAA et du MdT ont considéré que cette configuration pourrait être homologable pour le vol IFR. Le couplage, un par un, de chacun des axes de commande au directeur de vol a démontré que cette technique allégeait légèrement la charge de travail du pilote et on a jugé que le couplage à l'axe de commande de pas collectif était celui qui présentait le plus d'avantages.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

1.0 BACKGROUND

Historically, the realization of the helicopter's capability in performing instrument flight operations has been inhibited by two major obstacles. Inherent degradation in helicopter handling qualities at slow speed has resulted in a minimum speed limitation (Vmini) reflecting a limit in acceptable pilot workload and performance. Also, helicopter instrument operations were forced into a stereotypical fixed-wing operational scenario, primarily because of limitations in available approach aids and flight displays. Thus the unique capabilities of helicopters were not exploited and certification criteria tended to be based on these rather limited operational constraints.

In recent years, commercial pressures have caused an increased demand for operations into small heliports in more adverse weather conditions. The introduction of Micro-Wave Landing Systems (MLS) has demonstrated sufficient flexibility to cater to unique helicopter approach aid requirements. Efforts are being made to establish certification criteria which reflect these more demanding instrument flight operations, where the data base available for requirement definition is sparse.

1.1 Introduction

The Flight Research Laboratory (FRL) of the National Aeronautical Establishment (NAE) has been actively engaged in jointly funded experiments with the United States Federal Aviation Administration (FAA) since early 1980. These experiments, designed to address the improvement of helicopter IFR handling qualities, have been performed under Memoranda of Agreement with the FAA, the most recent one being A1A-CA-31. Reference 1 describes the previous phase of the program. This paper discusses the most recent phase of these experiments.

1.2 Scope of the Program

This phase of the experiments was designed to provide a data base for establishing certification criteria by investigating a number of options in pilot workload relief and performance enhancement. During the flight phase,

approaches were flown to low decision heights (50 feet) and low speeds (20 knots) representative of Category III A (zero ceiling, 700 feet visibility) operations, while on a six degree glideslope. The ground aids that were used represented an MLS installation including Precision DME, with glideslope and azimuth transmitters co-located at the landing site.

Three major objectives were defined at the outset of this experimental phase. The first objective was to document the handling qualities and certification implications created by the choice of crosswind compensation technique used by the pilot. The two possible techniques are: the crab method, where the rotorcraft is always flown in a coordinated manner and crosswinds are handled by heading changes; and the sideslip or wing-low method, where the rotorcraft heading is maintained as the inbound approach heading and crosswinds are handled by flying in an uncoordinated manner – sideslipping into any crosswind. Both were evaluated at various constant approach speeds and crosswind strengths. The second program objective was to investigate the benefits provided by various vertical axis (glideslope) display, guidance and control systems in the general environment of flight directed approaches. The three possibilities here were a raw glideslope data presentation, a collective/-glideslope flight director and, finally, a full coupling of the flight director control laws to the collective axis control, requiring no pilot action to maintain glideslope. The final objective of the program was to extend the concept of flight director control coupling to the other control axes to investigate possible workload benefits. Each of these three objectives was examined in the context of the low minima, decelerating approaches described above.

2.0 THE AIRBORNE SIMULATOR

The NAE Airborne Simulator is an extensively modified Bell 205A-1 helicopter with special capabilities that have evolved over the last decade (Figure 1 and 2). The special features derive from the fact that, the standard hydraulically boosted mechanical control actuators have been replaced by dual-mode electro-hydraulic actuators with servo-valves that can be positioned mechanically from the left (safety pilot) seat or electrically from the right

(evaluator pilot) seat full authority fly-by-wire station. Fly-by-wire inputs are generated by a set of motion sensors and a computing system consisting of two LSI 11/73 and one Falcon microprocessors, and D/A and A/D converters. Inputs to this system come from electrical controllers which may be either a conventional stick, pedals and collective combination with a programmable force-feel system or alternatively a 4-axis isometric force or deflection side-stick controllers. For this specific program conventional controllers were integrated with a variable force-feel system.

In order to improve the control response of the teetering rotor system on the airborne simulator, the stabilizer bar was removed as part of the original conversion to the simulation role. The longitudinal cyclic-to-elevator link was also removed at that time, and has been replaced with an electro-hydraulic actuator. For this program, however, the elevator was fixed in the neutral position. Reference 2 describes the NAE Airborne Simulator in detail.

In order to simulate instrument flight conditions visually, an IMC Simulator manufactured by Instrument Flight Research Incorporated, Columbia, S.C. was employed. The "simulator" consisted of goggles with lenses that incorporated liquid crystals to vary the goggle opacity. These goggles were worn by the evaluation pilot and were adjusted to provide a narrow field of unobstructed view with the remaining peripheral view highly obscured.

2.1 Cockpit Display

On all approaches, primary approach information was displayed in a combined form on the LED-matrix electronic attitude and direction indicator (EADI) shown in Figure 3. The 5 inch by 5 inch display consisted of light emitting diodes organized in matrix form with a density of 64 x 64 pixels per square inch. In this program, the display could be changed readily to provide three levels of display sophistication, namely, raw situation flight data, a two-cue flight director and a three-cue flight director. In the raw data display the roll, pitch and collective flight director symbols were not provided, whereas the collective flight director symbol was omitted in the two-cue flight director display.

On all approaches, the radio height box on the left of the display and the digits within the box flashed at 10 feet above decision height and remained flashing while below this height. An additional warning of decision height was provided in the form of an audio tone which came on at 10 feet above decision height and went off at decision height. When on a flight directed decelerating approach, an audio tone warned the pilot of the approaching deceleration when within 4 knots ground speed from the established profile, and terminated at the start of the deceleration profile.

3.0 APPROACH DESCRIPTION

The evaluation task in this program was to perform a 6° glideslope approach down to a 50 foot decision height. For each approach, the pilot was asked to consider only that portion of the approach from glideslope capture to the decision height at which point the safety pilot took over control of the helicopter. Since no definitive work exists on the performance criteria for such approaches, the limits for desirable and adequate approach performance, shown in Table 1, were based on the subjective opinions and evaluations of pilots who had participated in previous helicopter IFR experiments at NAE.

3.1 Deceleration Profile

All approaches were flown using ground speed calculated through a mixture of position and doppler ground speed measurements. The initial ground speed for a given approach was set by the evaluator to a predetermined value using a rotary switch on the approach control panel. This initial speed was the command signal which drove the speed flight director and error displays. On certain predetermined approaches the pilot also selected the deceleration profile through a switch on the approach control panel. On these occasions the command signal for the speed flight director and error displays was the initial ground speed until the actual helicopter ground speed and range to touchdown point intercepted the deceleration profile shown in Figure 4. At this point the commanded speed became the value given by the deceleration profile. To give a deceleration warning to the evaluator, an intermittent tone was provided in

the evaluator's headset when the helicopter ground speed initially came within 4 knots of the deceleration profile. This tone extinguished when the deceleration profile became the speed command signal. The profile itself corresponded to an approximately 0.045 G deceleration which appeared to the evaluator as a requirement to control speed by modulating pitch attitude about a relatively constant trim attitude.

3.2 Approach Guidance

A dual transponder microwave system was used to continually measure aircraft position relative to the touchdown point. In general this system provided position information at all altitudes above 50 feet throughout the approach area. Absolute accuracy of the steady state measurement of x,y position was on the order of 2 m. Localizer and DME quantities were calculated using this position information; and since the terrain in the approach area was relatively flat, radio altitude and DME were used to calculate glideslope position. This positional information was also used to calculate the artificial wind profiles which are discussed in paragraph 3.3.

At random intervals throughout the experiment, position signal dropouts were encountered. Using predictive algorithms based on last known position, doppler ground speed and heading, position information was obtained over these intervals however this predicted position was prone to slowly drifting to moderate glideslope and localizer error values. As depicted in Figure 5, a signal dropout, when encountered during an approach, would cause the pilot to track the predicted glideslope, localizer path and, upon regaining transponder signal, a tracking error would appear. When present in moderation, these randomly occurring tracking errors were found to be only barely perceptible to the evaluator pilots yet they provided enough 'noise' in the task to keep the tracking task at high priority. In a few instances where dropouts were subjectively judged to have created too large or too frequent tracking errors, the resulting evaluations were not considered valid.

3.3 Artificial Wind Profiles

To enable the evaluation of handling qualities limits resulting from the effect of crosswinds and crosswind shears encountered during the approach, and to provide realistically high workload levels on decelerating approaches, the majority of approaches flown during the experiment incorporated artificial crosswind profiles. In essence, these profiles required the pilot to follow approach paths which corresponded to the air mass track that would have occurred for a standard linear approach in the prescribed wind. For the simplified case of wind perpendicular to the standard linear approach, the lateral offset of the airmass flight path can be written as:

$$Y_{airmass}(x) = \int_{\xi=0}^{x} \left\{ W(\xi) / \sqrt{V^2(\xi) - W^2(\xi)} \right\} d\xi$$

where: $W(\xi)$ is the crosswind strength,

and

$V(\xi)$ is the aircraft ground speed profile,

both functions of distance from the touchdown point,

To place these offset approaches over the same physical area as the no-wind approaches, a heading bias ($\Delta\psi$) was added to the heading displayed to the pilot. For this case, $\Delta\psi$ was selected by

$$\Delta\psi = \mathrm{Tan}^{-1} \left\{ Y_{airmass}(X_s) \; / \; X_s \right\}$$

where $X_s = 3\ 1/2$ miles and the corresponding offset to the linear approach was calculated as:

$$Y_{offset}(x) = Y_{airmass}(x) - \left\{ \tan\Delta\psi \right\} x$$

The wind profiles ($W(\xi)$) selected for simulation were either a constant crosswind, the strength and direction of which was adjustable through a cockpit control, or a wind shear as depicted in Figure 6. Velocity profiles were either constant ground speed (30, 40, 50, 60 or 70 knots) or the deceleration profile described in section 3.1

Since it was unlikely that evaluations would take place in conditions of no ambient wind and it was equally unlikely that each evaluator would precisely

track both the ground speed and lateral approach profiles, the wind encountered on a particular approach differed from the selected artifical profile and was calculated after the flight. This "encountered" wind was a sum of the ambient wind measured by the aircraft, the particular artifical wind profile selected for the given approach and the effect of deviations from the selected profile caused by aircraft ground speed errors.

The encountered wind, W_E, can be written as

$$W_E(t) = W_m(t) + W_s(t)$$

where W_m is ambient lateral wind component measured by the aircraft and,

W_S is the simulated wind encountered which is very well approximated by

$$W_s \sim V_t \cos\left\{\tan^{-1}\left[\frac{\partial Y_{airmass}}{\partial \xi}\right]\right\}$$

where $\dfrac{\partial Y_{airmass}}{\partial \xi}$ is given by equation 1,

and

V_t is the actual aircraft ground speed.

While the techniques described here provide exact reproductions of the wind for constant crosswind and constant ground speed approaches, which constituted one part of this experiment, the technique is not exact for cases involving either decelerating approaches or wind shears.

In both real and artificial wind cases the airmass velocity vector with respect to the vehicle is identical so in both cases the aerodynamic forces and moments caused by relative motion between the airmass and vehicle are identical. Unfortunately to replicate this airmass vector the vehicle is required, in the case of varying simulated wind and ground speed, to alter its inertial velocity. This alteration requires additional inertial forces which would not be present in the real wind case. Using a simplified mathematical model of

the Bell 205, one can calculate that for the extreme case of simulating a 40 knot per 1000 vertical feet lateral wind shear at 60 knots ground speed, these inertial forces account for roughly 12% of the total forces experienced. Since crosswind shears were provided to increase the workload of the approach tracking task, these excess inertial forces serve as a conservative factor in the overall results for decelerating approaches with wind shears. This conservative factor is not present in the constant speed, constant crosswind approach results nor is it in any evaluation where lateral acceleration levels were considered the result.

4.0 FLIGHT DIRECTORS

Flight directors were available in each of the three control axes, pitch, roll and collective, to ease the workload of controlling speed, and position with respect to the localizer and glideslope. To be consistent with low speed helicopter operations, these directors were based on "back sided" technique - that is control of speed by longitudinal cyclic and control of height (or glideslope) by collective. Each single axis director was originally designed using error and error rate feedbacks, along with selected aircraft state feedbacks, to provide "k/s" behavior between pilot input and flight director response*. The stability derivatives used in this initial design were consistent with those found in Reference 3 but were augmented to the angular rate damping levels implemented on the aircraft for this series of evaluations (see Section 5.0). Each flight director axis was optimized through evaluation on the ground and in flight. The following sections discuss the finalized design used for each axis.

4.1 Pitch Flight Director

The block diagram of the pitch flight director is included as Figure 7. As depicted in the Bode plots of the transfer function FD_θ / δ_e (Figure 8), this

* k/s behavior is characterized by the output (flight director position) responding like an integral of the input (control deflection).

director behaves like a simple integration of the longitudinal cyclic (k/s) over the entire frequency range of pilot control. The pitch limiter in the forward path, set at ± 10 degrees around the trim pitch angle of approximately ± 5 degrees, provides a necessary angular limit to speed corrections when errors become large. The pitch angle to speed scaling of this director, K_1, was 1 degree per knot of steady state error. Overall scaling of the director was 0.43 inches of symbol movement per 10 knots of steady state error.

4.2 Roll Flight Director

Similar to the pitch flight director, the roll flight director used error $(y - y_C)$, error rate ($\dot{y}$) and aircraft angle (ϕ) to create a k/s transfer function of $FD_\phi / \delta_\partial$. The block diagram and Bode plots of the transfer function at 40 and 60 knots are shown in Figures 9 and 10. Roll angle scaling was set at approximately 1/2 degree per foot of steady state localizer error. Overall flight director scaling was 0.30 inches symbol movement per 100 feet of steady state localizer error. The washed out $K_1 y + \dot{y}$ term in the $K \dot{y}$ path is a complimentary mix of y and $\dot{y}$ which alleviates flight director problems caused by steady offsets in the $\dot{y}$ measurement. The limiter in the Ky path provides a maximum 30 degree heading intercept to localiser when localizer error is large. The second limiter provides a ± 30 degree boundary on commanded roll angle. Despite the perception that the use of crab vs sideslip technique would significantly alter the requirements for a roll flight director, both a theoretical analysis and preliminary in-flight evaluations demonstrated that this flight director performed equally well when using either technique.

4.3 Collective Flight Director

Unlike the pitch and roll flight directors, the final collective flight director configuration on this program did not exhibit k/s behavior. Initial flight evaluations of the k/s design showed that this director was exceptionally difficult to center at moderate to large levels of glideslope error and provided little subjective improvement over a raw glideslope data presentation. While pilots were satisfied with control of closure rate of the display symbol to zero with pitch and roll axes, pilot technique and comments regarding the collective

axis during preliminary evaluations suggested a lower level of attentiveness to collective inputs and led the design of the collective director toward incorporation of substantially more collective lead information. Ground based simulations in the absence of turbulence and with perfect consistancy between all data inputs led to a vertical acceleration feedback path for satisfactory flight director behavior. This director design could be referred to as a collective position director since the acceleration feedback served to predict the steady state error closure rate for a specific collective input prior to achieving that steady state rate of ascent or descent. Since vertical acceleration is an impractical feedback in the presence of turbulence and aircraft structural noise when high frequency information is required, a washed out collective position signal, with the first order break point roughly corresponding to the aircraft Zw derivative, was used in the final design.

The block diagram of the final collective flight director, Figure 11, shows the collective position feedback loop and a limiter on the glideslope error term. This limiter bounded the commanded intercept rates of descent to be within 600 ft/min of the steady state trim descent rate, $\dot{h}_C$. For a constant 60 knot 6° glideslope approach, nominally requiring a descent rate of 635 ft/min, these limits correspond to aircraft descent rates ranging from 35 ft/min to 1235 ft/min. The Bode plots of the $FD\delta_C / \delta c$ transfer function at 40 and 60 knots (Figure 12) demonstrate a constant amplitude ratio over the normal frequency range of pilot control, consistant with the collective position director concept. Overall scaling of the director was approximately 0.25 inches symbol deflection per 25 feet of steady state glideslope error.

5.0 SIMULATOR STABILITY AUGMENTATION AND CONTROL MODES

5.1 Evaluation Pilot Control Characteristics

The analog control force feel system of the airborne simulator was set up to provide 1/2 lb breakout and 1/2 lb/in stick force gradient for pitch and roll axes. A slow rate trim for pitch and roll was provided through a "coolie hat switch" on the control column. No trim force release function was provided.

The collective lever was a typical adjustable friction type with no force gradient or perceptible breakout force. Since all evaluations were performed without the need for yaw pedal inputs, the pedal force feel system was not documented.

5.2 Stability Augmentation

The only augmentations of stability provided to the basic airframe for this series of tests were rate feedback loops to augment pitch and roll rate damping levels (Mq and Lp) of the helicopter. Bode plot analysis of frequency sweeps in pitch and roll at 40 and 60 knots resulted in the estimates of rate damping level depicted in Figures 13 and 14. These augmented levels of approximately - 2.0 sec^{-1} bring the Airborne Simulator into the domain of present day IFR helicopters, such as the Sikorsky S-76.

Theoretical analysis of the longitudinal axis characteristics of the aircraft, with pitch rate feedback sufficient to attain the measured Mq value, resulted in an aircraft phugoid period estimate of 30-60 seconds (dependent upon assumptions) with no apparent phugoid damping at 60 knots. This estimate correlates well with a flight recorded phugoid mode period of 45 seconds at 60 knots with no measurable damping. The longitudinal axis root loci for 20, 40 and 60 knots airspeed, showing the rate damping augmentation closed loop poles, are plotted along with the dynamic stability boundaries of current FAA requirements for helicopter instrument flight below Vmini (Reference 4) in Figure 15. It should be noted that all poles are within the FAA bounds and that the rate damping augmentation loop effectively eliminates the short period mode of the aircraft.

5.3 Yaw Axis Control Modes

Two basic modes of yaw axis control were implemented and evaluated in this experiment, turn coordination and heading hold. Both modes alleviated the need for pilot yaw pedal inputs and pilots were instructed to fly these modes "with their feet on the floor". The architecture of each of these modes was not intended to mimic systems currently in place on IFR helicopters but rather to

provide the best possible performance in their selected tasks. The use of turn coordination or heading hold mode coincided with the choice of crosswind compensation technique chosen for a given evaluation. For crab technique approaches the turn coordination mode relieved the pilot of yaw axis stabilization and control. Similarly the heading hold mode, locked onto the approach heading, provided the same workload relief for the sideslip technique approach. A brief description of each mode and of the method of mode selection follows.

5.3.1 Turn Coordination Mode – This mode was the "default" configuration and was engaged at all times except when heading hold was selected. A block diagram of the architecture of the turn coordination mode is included as Figure 16. The typical pilot performance when using this mode is shown in Figure 17 for a 60 knot decelerating approach through a 35 knot crosswind shear. While not outstanding, the performance of the turn coordination mode did allow all evaluation pilots to completely disregard the yaw axis of the aircraft and fly with their "feet on the floor."

5.3.2 Heading Hold Mode – The heading hold mode of the helicopter was manually selected by the evaluation pilot by depressing a switch on the control stick hand grip. Upon actuation this mode used the helicopter heading at the moment of engagement as reference heading and in general was able to maintain this heading to within 5 degrees, irrespective of lateral cyclic input. Flight in this mode was subject to a sideward velocity limitation imposed subjectively by the safety pilot. Typical imposed limits were on the order of 35 knots.

The control system architecture of this mode was based on a theoretical state space model of the Bell 205 and the design used the Linear Quadratic Regulator technique. A block diagram of this system and a plot of system performance while traversing a 25 knot crosswind shear during a 60 knot decelerating approach are shown as Figures 18 and 19.

5.3.3 Yaw Axis Mode Blending – In addition to the manual selection of heading hold mode discussed in the previous section, a turn coordination/heading hold blended mode was also available. When selected, this mode enabled the crab approach technique until the helicopter decelerated through a pre-selected ground speed, at which time the yaw axis mode changed from turn coordination to heading hold, locking up on the last helicopter heading while in turn coordination mode as the reference heading. For the remainder of the approach the constant heading required the use of the sideslip technique. The ground speed selected for this blend was normally between 30 and 50 knots. An example of this mode blending on a decelerating approach through a wind shear is included as Figure 20.

5.4 Control Axis Coupling

In addition to manual control of pitch, roll and collective axes of the helicopter, control coupling modes were available to automatically satisfy the flight director in the axis chosen. These coupled modes, available for each axis separately or in any combination of control axes, provided the pilot with a workload reduction and maintained the desirable performance standard required in the selected axis in terms of glideslope, localizer or speed error. These coupled modes were mechanized by applying a simple gain to the flight director error and feeding the resulting signal to the relevant control axis. A slight augmentation of roll damping in the lateral coupled mode was required to alleviate lateral divergence for flight in turbulent conditions. The performance plot in Figure 33 demonstrates the accuracy of these coupled modes by showing the glideslope, localizer and speed errors for a fully coupled (all axes) decelerating approach through windshear. This plot also confirms the basic performance of the flight director in each axis.

6.0 EXPERIMENTAL PROCEDURES

Evaluations were flown by five subject pilots, two helicopter certifcation pilots and one operational pilot from the FAA, a helicopter certification pilot

from Transport Canada, and a research helicopter pilot from the NAE. A summary of relevant experience is included in Figure 21.

Each evaluator was thoroughly briefed on the experimental objectives, flight task, aircraft characteristics and control modes and display layout. To improve pilot proficiency with the flight director and display, each evaluator was given one to two hours of ground based simulation of the approach task using the actual aircraft in a fixed-base simulator mode. Following this, each evaluator was provided with up to three hours of training time in flight to become familiar with the task, display and control configurations. During the evaluations, the particular configuration flown on each approach was known to the evaluator, but the form and extent of any simulated winds was unknown prior to flying the approach. Each pilot performed 5 or 6 evaluation sorties and, in total, approximately 180 approaches were evaluated.

6.1 Minimum Speeds for Crab Technique Approaches

One sortie for each evaluation was flown to ascertain whether a minimum speed existed below which the crab technique, utilizing the automatic turn coordination/sideslip suppression mode, became unacceptable. Pilots were requested to fly constant speed approaches, using the 3 cue flight director, with each approach flown at a different ground speed down to 30 knots. Each approach was flown in conditions of simulated adverse windshear.

6.2 Maximum Sideforces Tolerable during Sideslip Technique Approaches

Each evaluator flew two sorties of constant speed, sideslipping approaches using the 3 cue flight director and the heading hold control mode. On the first sortie with a fixed crosswind condition, approach speeds were varied between a minimum of 30 knots to a maximum of 70 knots. On the second sortie, the evaluator flew constant 60 knots ground speed approaches where a different simulated wind condition was supplied on each approach. In addition to providing the standard ratings, pilots were also asked to rate the sideforces experienced during the final segment of the approach after glide-slope and localiser capture as "not noticed", "noticeable" or "objectionable".

6.3 Decelerating Approaches

The pilots were also tasked with the evaluation of a number of display and control configurations while performing decelerating approaches to 20 knots groundspeed (from 60 knots) and 50 foot decision height. The following configurations were investigated:

a) Crab technique - 3 cue flight director,
b) Sideslip technique - 3 cue flight director,
c) Crab technique blending to sideslip technique - 3 cue flight director,
d) Crab technique blending to sideslip technique - 2 cue flight director, (no collective flight director)
e) Fully coupled approach (crab technique) - 3 cue flight director,
f) Coupled collective - pitch and roll flight directors,
g) Coupled pitch - collective and roll flight directors,
h) Coupled roll - collective and pitch flight directors, and
i) Crab technique with raw data display of glideslope, localizer and speed.

In all cases the crab technique approaches used the automatic turn coordination mode while sideslip approaches used the automatic heading hold mode.

6.4 Wind Conditions During the Evaluations

Approaches were flown in ambient wind conditions with on-track components varying from 10 to 15 knots tailwind, to 10 knots headwind, and crosswind components of up to 20 knots. No significant natural wind shear was present. When required, ambient wind conditions were augmented using the method described in Section 3.3.

6.5 Questionnaires

Following each approach, the evaluators completed a questionnaire shown in Figure 22. As is evident on this form, four subjective ratings were required from each evaluator on each approach. These were:

a) An overall handling qualities rating from the Cooper/Harper Rating Scale, shown in Figure 23;

b) A certification level assessment, shown in Figure 24;

c) A workload assessment shown in Figure 25; and

d) An assessment of sideforce characteristics when relevant, as shown in Figure 22, question number 5.

7.0 RESULTS

7.1 Subjective Assessment of Crab Technique Approaches at Various Speeds

The handling qualities degradation with decreasing approach speed was minimal for crab technique approaches. At 50 knots the mean Cooper/Harper rating was 3.1 with variations from 2 to 4. At 30 knots the mean Cooper/-Harper rating was 3.25 with variations from 2 to 4. All approaches were rated as certifiable, with 50% of the certification assessments rated as adequate for single pilot operation. It is expected, however, that the overall suitability of this approach technique will be governed by the visual orientation of the landing pad at breakout rather than handling qualities issues. Since the forward field of view at large crab angles is largely dependent on specific helicopter geometry, this issue was not addressed during this experiment.

7.2 Subjective Assessment of Sideforce Characteristics during Sideslip Technique Approaches

Figure 26 depicts the average lateral accelerations experienced for various approach and crosswind speeds encountered during evaluations of the sideslip approach technique. Figure 27 shows the subjective pilot opinion of the experienced sideforces in terms of the three rating levels – not noticed/-noticed/objectionable. From this representation it appears that the objectionable sideforce threshold, based on a 50% rating level, would be 0.07 g, which corresponds to a steady state bank angle of approximately 4 degrees. As depicted in Figure 26 this limit appears independent of crosswind direction (left or right) or of the forward velocity for the Bell 205A and corresponds to a lateral velocity of 24 knots (40 ft/second). Trim tail rotor pedal position for these conditions are 30% and 40% from the zero sideslip trim position for left and right sideslips respectively.

7.3 Subjective Assessments of the Decelerating Approaches

The subjective ratings, i.e., Cooper/Harper, Workload and Certification Assessments determined during the decelerating approaches will now be discussed. These ratings represent only those approaches where subjectively acceptable sideforces were experienced in crosswinds or windshear, i.e., maximum of .07 g in a lateral direction.

7.3.1 Handling Qualities Ratings – The handling qualities ratings of decelerating approaches which were outlined in paragraph 7.3 are shown in Figure 28 as the subjective rati g (Cooper/Harper or modified workload) versus configuration. The vertical lines signify the spread of Cooper/Harper or workload ratings with the symbol representing the average rating between evaluators. Because all evaluators did not fly an equal number of approaches with a particular configuration, the average values shown here were obtained by taking the individual evaluator's average for a given configuration and then determining the overall average of the individual averages for the configuration.

It is evident from Figure 28 that all approaches with any single axis coupled, with blended crosswind technique (at 45 knots) (configurations 1, 3, 4) were rated, in most cases, as Level 1 on the Cooper/Harper scale, with a slight preference given to the configuration with the roll axis coupled. The reader must be cautioned, however, that the incremental improvement of these configurations over some of the configurations to be discussed was indeed very slight. Since for pitch or roll coupling the pilot still must control the other cyclic axis some evaluators saw little benefit of such workload relief and alluded to a lack of control harmony when using this technique. The minimal difference in ratings between configurations 5 and 6 suggests that the collective flight director provides only a slight handling qualities improvement over raw glideslope 2-cue flight director approaches. Workload ratings also confirm this trend.

7.3.2 Certification Assessments – In discussing certification philosophy with the evaluators, it was apparent that little common ground exists in determining whether a certain configuration required a crew of one or two, even though it was definitely certifiable. Table 2 illustrates the number of single vs two pilot certification assessments received from the evaluators of this experiment. Since each pilot flew roughly the same configuration matrix, the table demonstrates a disparity between pilots on the minimum requirements for single as opposed to two pilot ratings. Figure 29 shows the single pilot and two pilot data plotted against the handling qualities rating, where no disparity seems to be present. At this time the disparity shown in certification assessments is attributed to the differing pilot backgrounds (research, certification, or operational) and an inconsistent view of what factors should be considered during this judgement. Although the task as flown required only tracking localizer, glideslope and speed errors some pilots were reluctant to provide single pilot assessments when addressing an operational scenario. The level of excess workload required for auxiliary tasks (i.e. emergencies) when on final approach was not standardized between

evaluators. In some cases evaluators were suspected to be following the rule that if a flight director is used, a second pilot is required to monitor raw data.

Figure 30 summarizes the percent of assessments rated as single-pilot, two-pilot or uncertifiable for each configuration. Some correlation is evident where more difficult configurations resulted in a larger percentage of two pilot or uncertifiable ratings. Uncertifiable ratings were evident in only two configurations, where sideslip approach was flown throughout the approach (11%) and when only raw localizer, glideslope and speed errors were displayed to the pilot (67%). This last configuration would be clearly uncertifiable.

Figure 31 shows the uncertifiable rating trend plotted against the handling qualities rating. This plot suggests a 6-7 Cooper/Harper rating as the decision point for certification. This 6-7 decision corresponds to the judgement of whether adequate performance is attainable with tolerable pilot workload.

8.0 APPROACH TRACKING PERFORMANCE

The plots in Figures 32 to 42 provide composite plots of error in speed, localizer and glideslope for a particular configuration. Two display system errors are evident from these plots. Significant biases in speed error on some approaches are due to a system error in selecting the required reference speed. Also, sharp discontinuities in localizer and glideslope errors, when evident, are the result of trisponder signal dropouts, with the predictive algorithm washing this error out, as discussed in paragraph 5.0.

8.1 Constant Speed Approaches

8.1.1 Crab Technique – Constant speed approaches were included in the matrix to indicate a comparison in performance between these approaches and the decelerating manoeuvres. Figures 32 to 34 indicate

errors in the three performance parameters when flying constant speed approaches (30 to 50 knots) using crab technique. When one accounts for the display bias in speed error, mentioned in 8.0 above, this parameter was generally tracked to ± 3 knots. Localizer and glideslope were tracked to ± 20 feet. No degradation in performance is apparent at the lower reference speeds, supporting the results discussed in section 7.1.

8.1.2 Sideslip Technique – Figure 35 is an error plot for sideslip approaches at a constant speed of 50 knots. With the exception of the localizer error on one approach, errors are very similar to those discussed above.

8.2 Decelerating Approaches

8.2.1 Approaches with Coupling – Figures 36 to 39 are error plots of the approaches where one or more axes were coupled. Pitch, roll and collective were coupled in Figure 36. Rather pronounced speed bias errors are evident on this plot, but when these are taken into account, errors of ± 3 knots were easily maintained, the largest speed error developing during the initiation of the deceleration. On this rather limited sample size, localizer and glideslope were maintained to ± 15 feet.

The remaining three plots, where a single axis is coupled, indicate that the most pronounced improvement in performance occurs with the collective coupled, where glideslope errors are reduced from ± 35 feet to ± 15 feet.

8.2.2 Two Cue Flight Director-Raw Data Collective – Figure 40 is a plot of errors when using a two cue flight director, where collective control was used to null out raw glideslope data. This limited sample size indicates that glideslope errors were contained to within ± 25 feet after the deceleration was initiated.

8.2.3 Three Cue Flight Director - Crab Technique Blending to Sideslip Technique – Figure 41 is included to indicate the errors that can be expected when the pilot controls all three axis with a three-cue flight director in decelerating approaches. Speed errors were $\pm$ 3 knots, localizer $\pm$ 20 feet, and glideslope $\pm$ 30 feet.

8.2.4 No Flight Director - Raw Information Only – Figure 42 shows the errors in speed, localizer and glideslope on approaches flown without the aid of a flight director. The large errors are evidence that these approaches would not be acceptable.

9.0 CONCLUSIONS

1. For crab technique approaches, i.e. no sideslip, in crosswind shear conditions, handling qualities did not degrade significantly with decreasing approach speeds and certifiability was also unaffected. The offset of the landing area from the aircraft longitudinal axis in high crosswinds is a concern yet to be addressed.

2. When flying sideslip approaches in steady crosswinds, pilots generally displayed an acceptance of steady state bank angles up to 4° (lateral acceleration of 0.07g). The 0.07g limit, regardless of helicopter type, should be considered the maximum steady state level which can be tolerated in this type of IFR approach.

3. Certification assessments, workload assessments and handling qualities ratings for decelerating 6° approaches to 50 foot decision height tend to slightly favour the crab technique over the sideslip technique. The blended crab/sideslip technique assessments are similar in almost all respects to the pure sideslip approach assessments. In either case, however, the rotorcraft was judged to be IFR certifiable and to possess borderline Level 1 handing qualities.

4. When performing decelerating approaches to the limits imposed here, 50 feet and 20 knots, the addition of a flight directed display was considered

essential. Provision of a two-cue flight director (pitch attitude for speed, roll attitude for azimuth) allowed certifiable ratings, but these were slightly improved with the addition of the third cue (collective for height).

5. Automatic coupling of a single axis (pitch, roll or collective) to the flight director resulted in a slightly improved pilot workload and performance from a mean Cooper/Harper rating of 3.4 to 3.0 for decelerating approaches with blended yaw axis control (crab technique blending to sideslip technique). Despite perceived differences in single axis tracking workload, the subjective ratings of the various single axis coupled configurations show no significant difference between configurations. Pilot comments suggest however that since the pilot would always have to control at least one cyclic axis, the collective coupling to the flight director provides the most sensible implementation.

10.0 ACKNOWLEDGMENT

The authors are grateful for the contributions made by the following evaluators in providing their expertise and judgements during this program:

Eric Bries	-	FAA Southwest Region
Paul Faidley	-	FAA Southwest Region
William Jupp	-	Transport Canada, Ottawa
Roy Lockwood	-	FAA New England Region
Murray Morgan	-	NAE Ottawa

11.0 REFERENCES

1. Kereliuk, S., Sattler, D.E., "Determination of Handling Qualities and Display Requirements for Helicopter Instrument Flight During Decelerating Approaches to Slow Speeds", National Research Council Canada, NAE-AN-44 NRC No. 27720, May 1987.

2. Sattler, D.E., "The National Aeronautical Establishment Airborne Simulation Facility", National Research Council Canada, NAE Misc. 58, May 1984.

3. Heffley, Robert K., Jewell, Wayne F., Lehman, John M., VanWinkle, Richard A., "A Compilation and Analysis of Helicopter Handling Qualities Data, Volume One: Data Compilation", NASA CR3144, August 1979.

4. Code of Federal Regulations Part 27, Appendix B and Part 29, Appendix B. January 1, 1985.

	Desired	Adequate
Speed	5 knots	10 knots
Localiser	50 ft.	100 ft.
Glideslope	12 1/2 ft.	25 ft.

TABLE 1: Approach Performance Standards

PILOT	ONE PILOT OK	TWO PILOTS REQUIRED
1	0	33
2	18	6
3	1 marginal	22
4	32	20
5	1 marginal	19

TABLE 2: Single vs Two Pilot Certification Ratings

FIG. 1: THE NAE AIRBORNE SIMULATOR

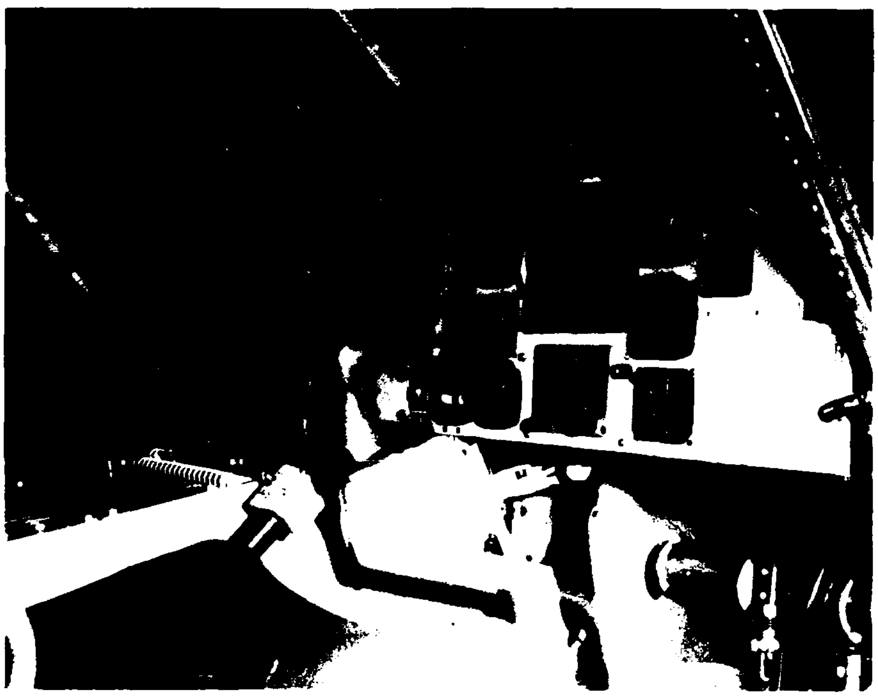

FIG. 2: EVALUATION PILOT STATION

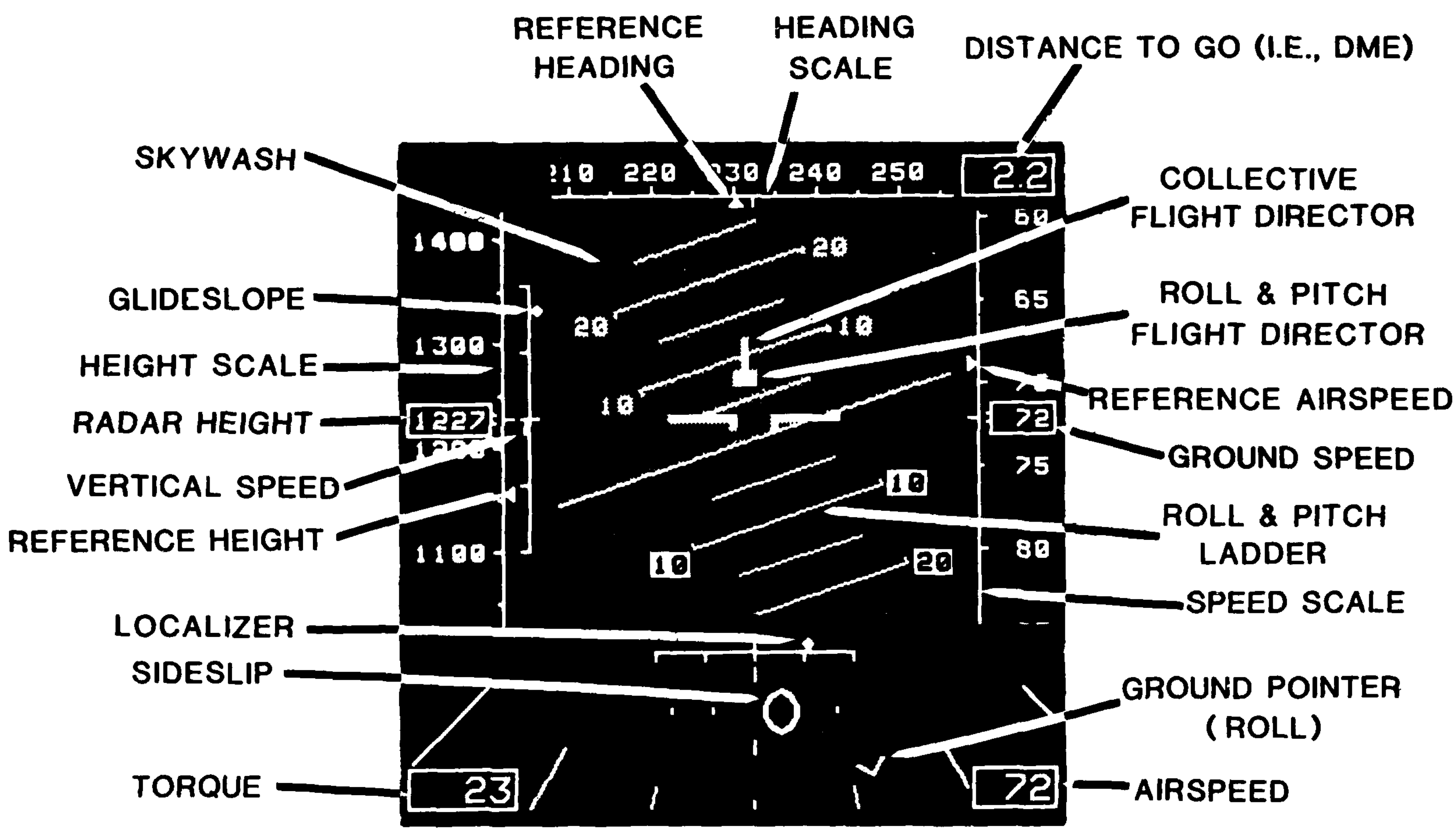

FIG. 3: PROGRAMMABLE, FLAT-PANEL ELECTRONIC DISPLAY

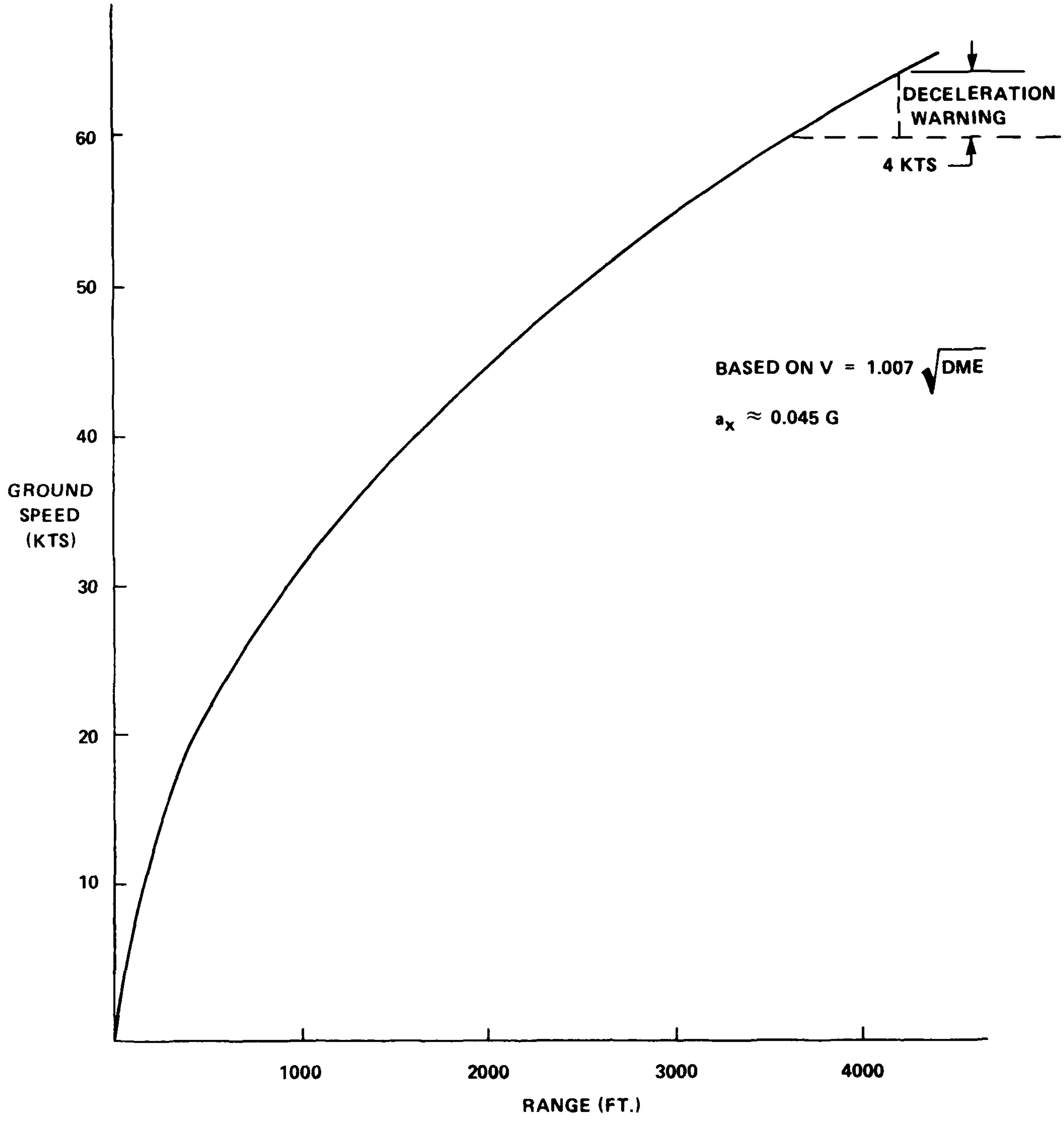

FIG. 4: DECELERATION PROFILE

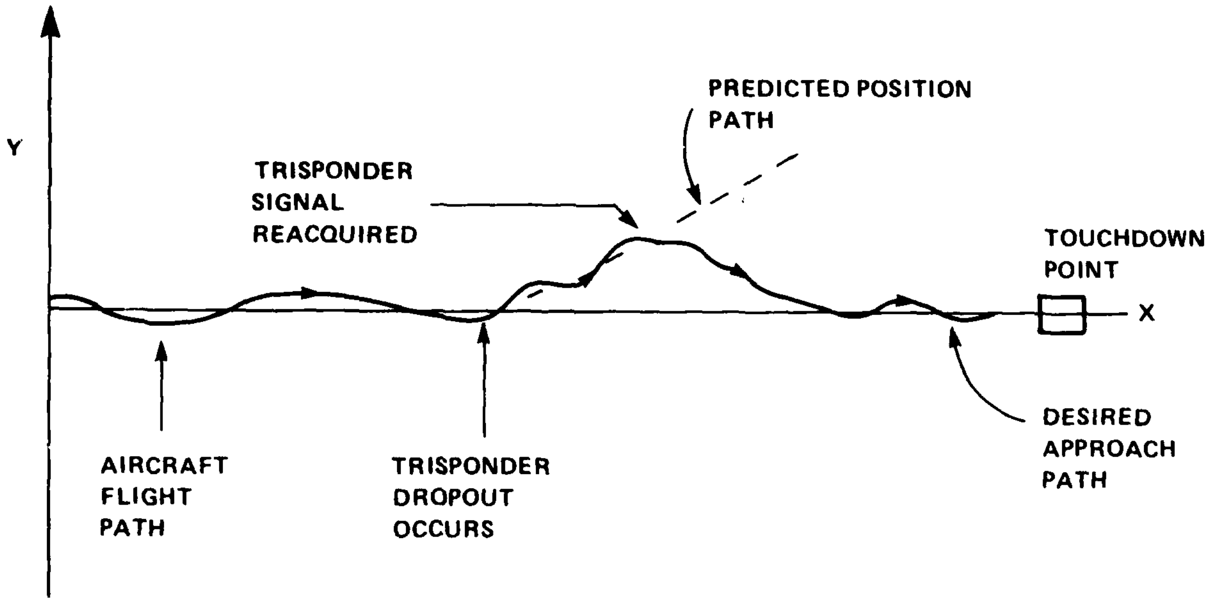

FIG. 5: SAMPLE TRISPONDER DROPOUT

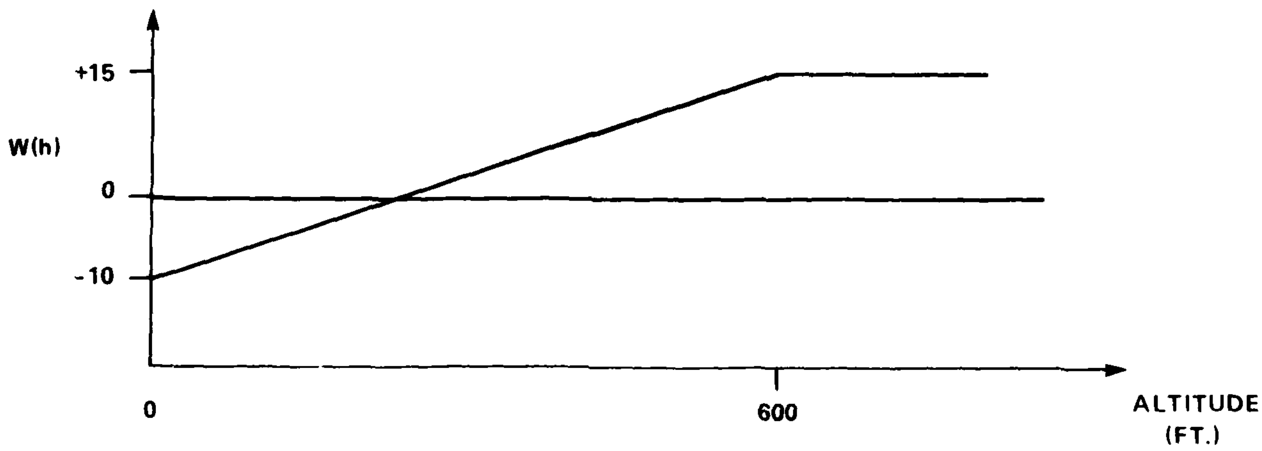

FIG. 6: SIMULATED WIND SHEAR

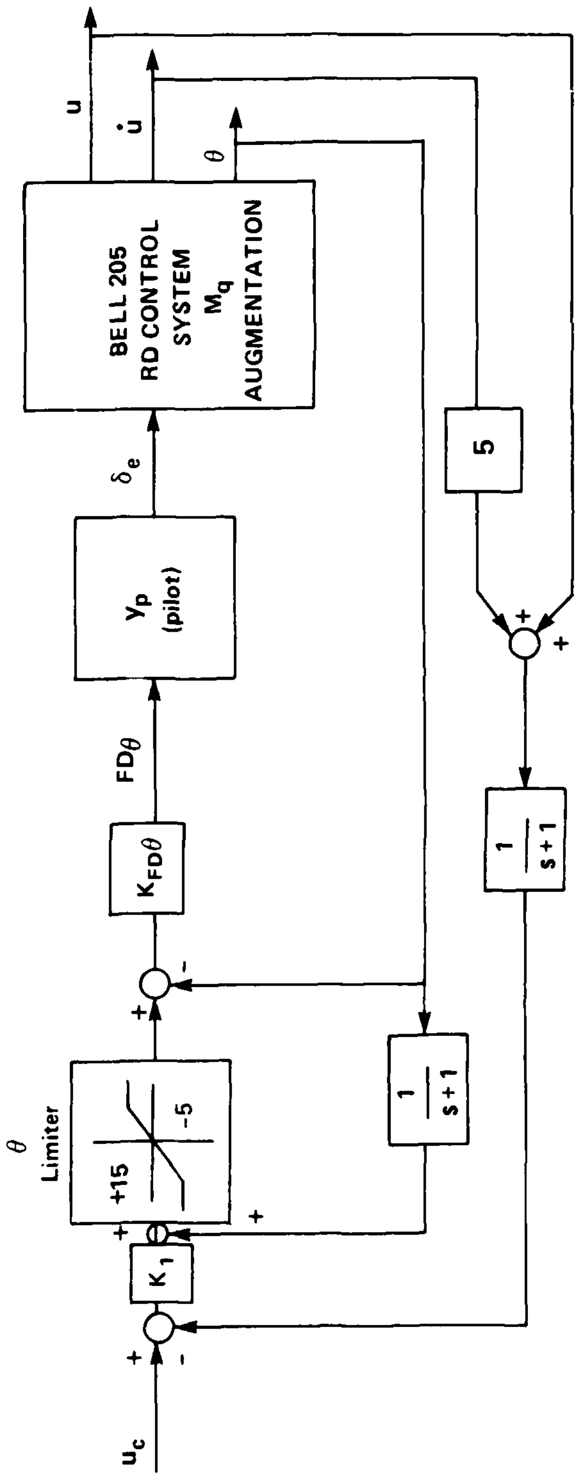

FIG. 7: PITCH FLIGHT DIRECTOR

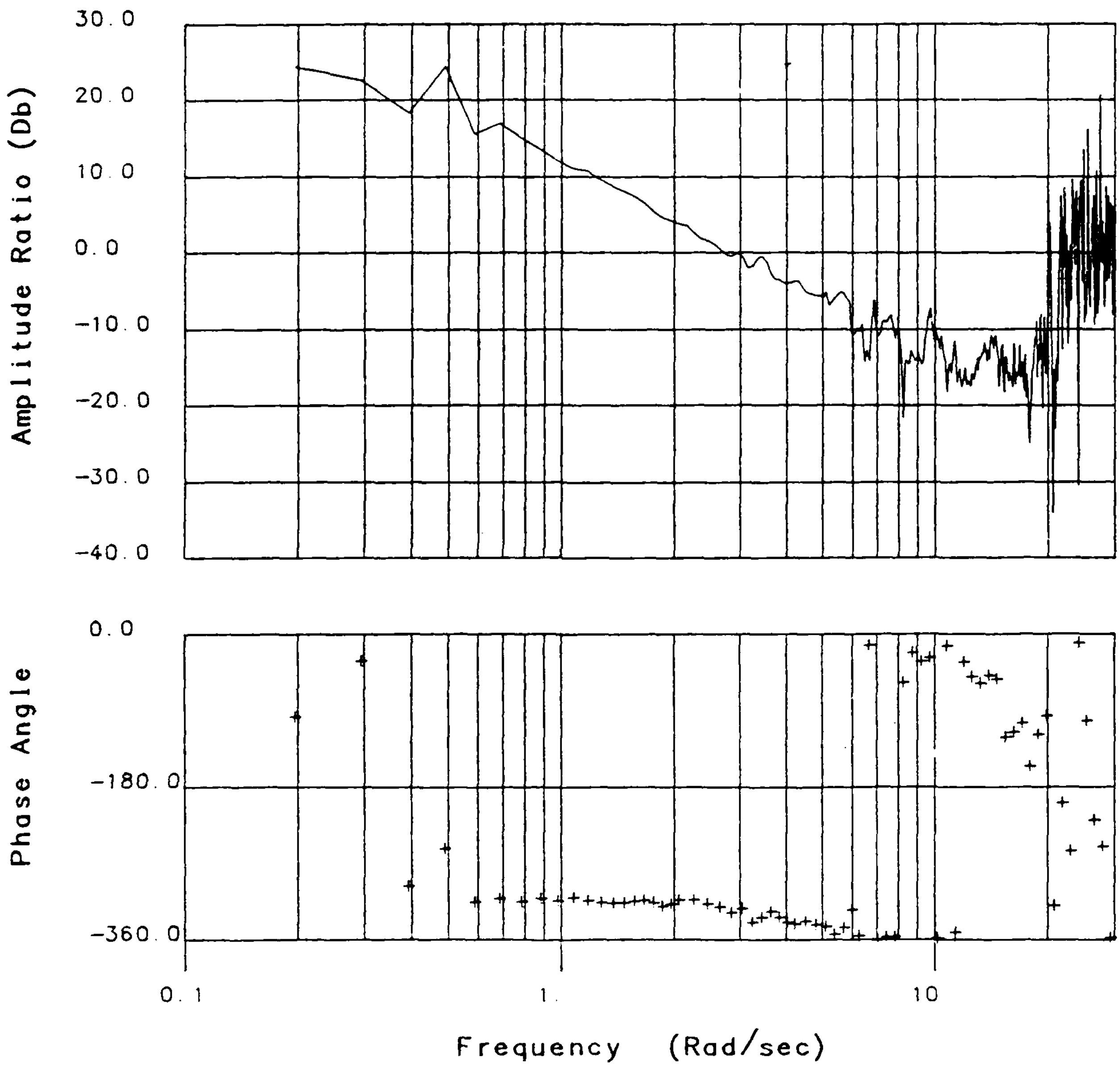

FIG. 8: BODE PLOT: PITCH FLIGHT DIRECTOR/DELTA *e* '40 KTS)

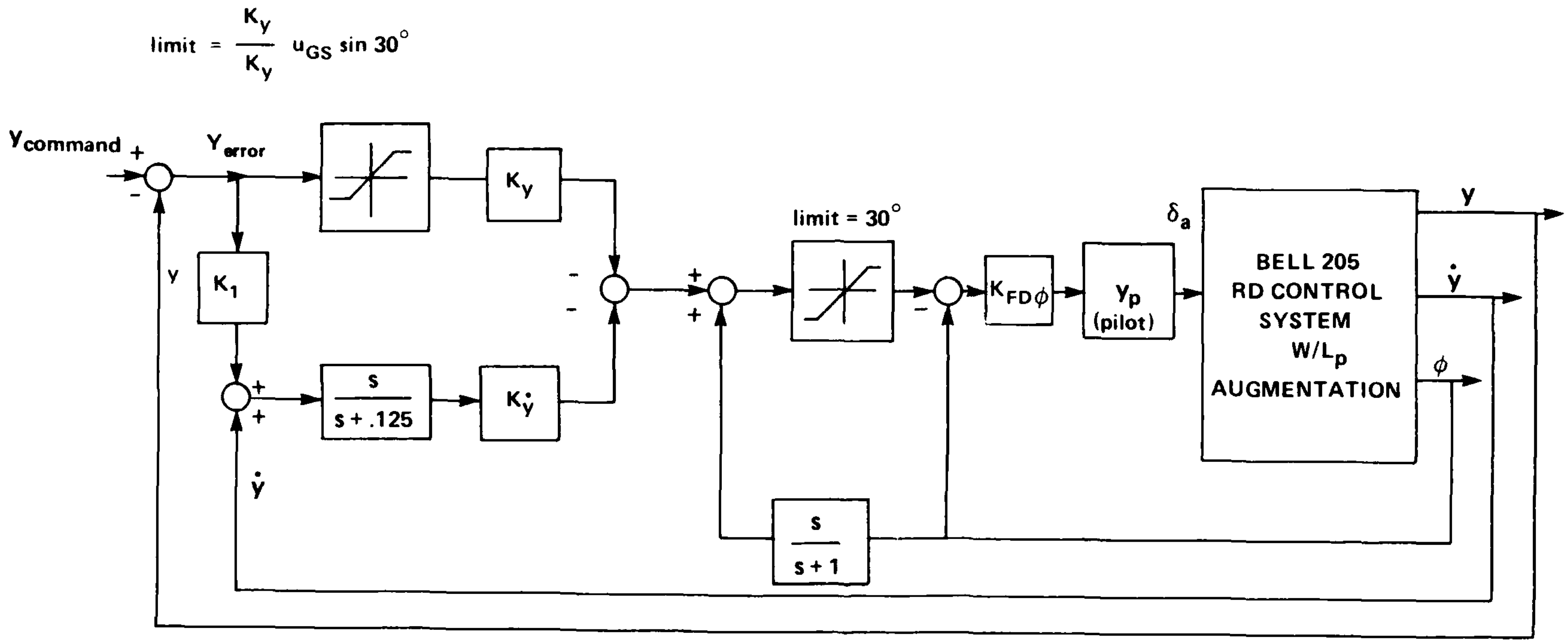

FIG. 9: ROLL FLIGHT DIRECTOR

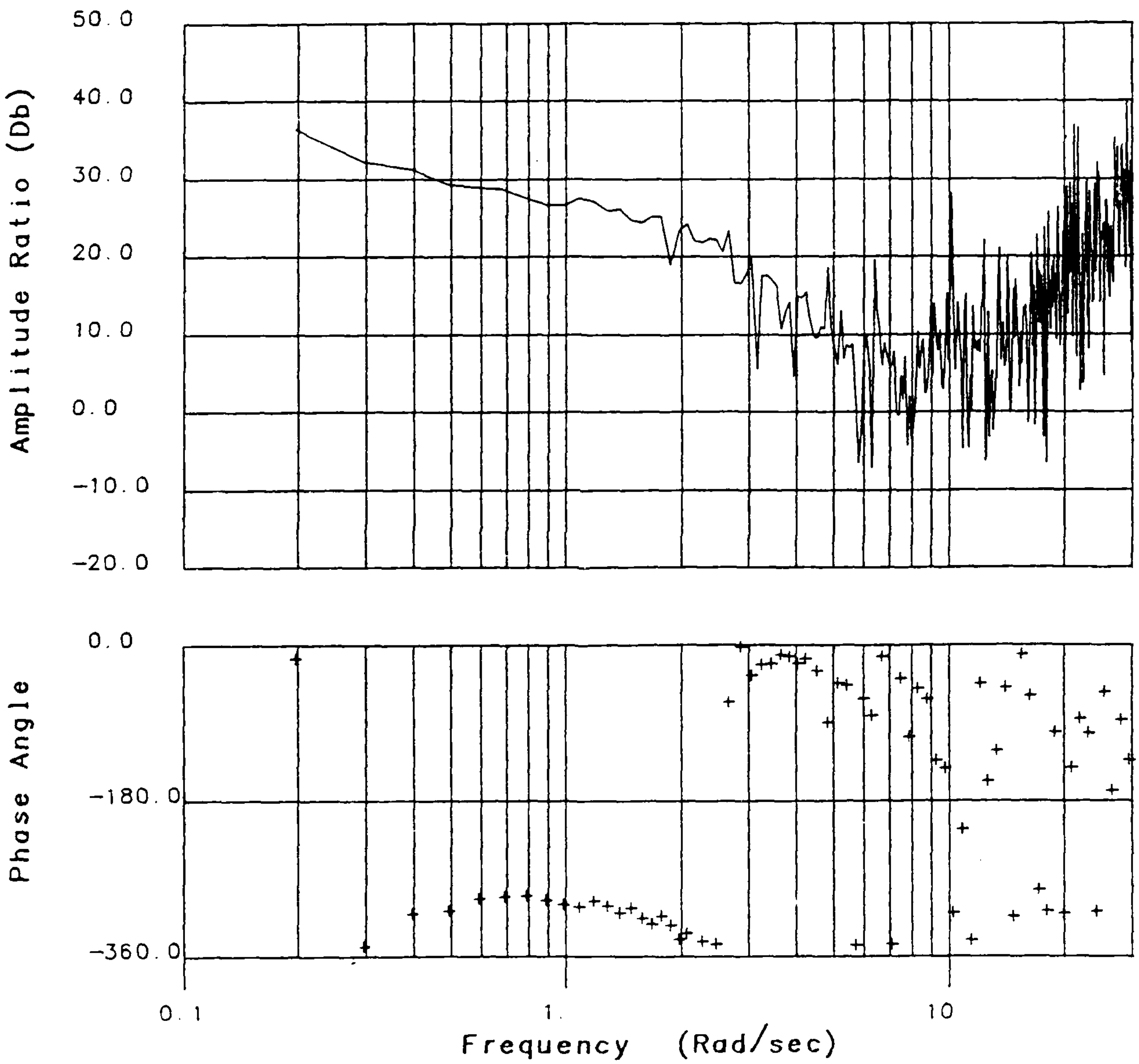

FIG. 10: BODE PLOT: ROLL FLIGHT DIRECTOR/DELTA a (40 KTS)

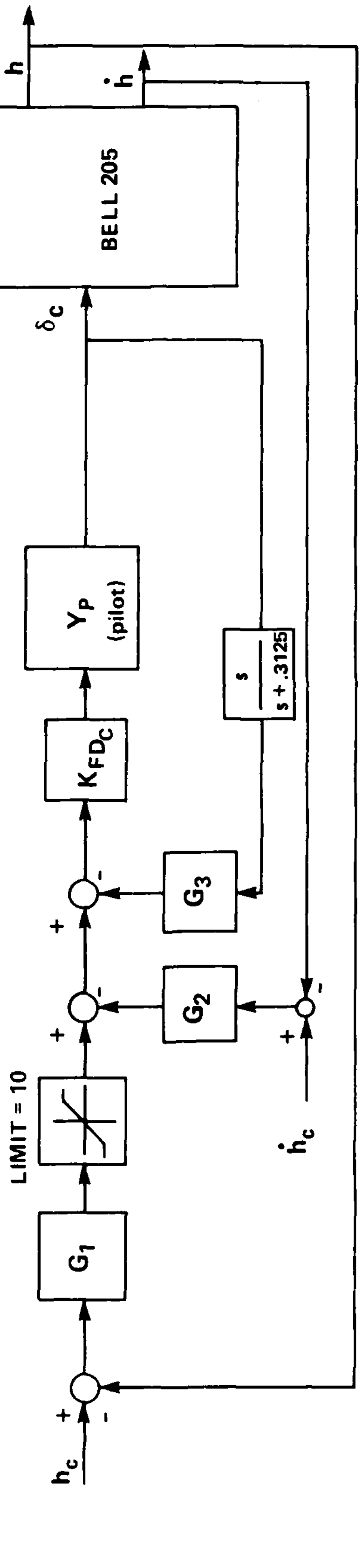

FIG. 11: COLLECTIVE FLIGHT DIRECTOR

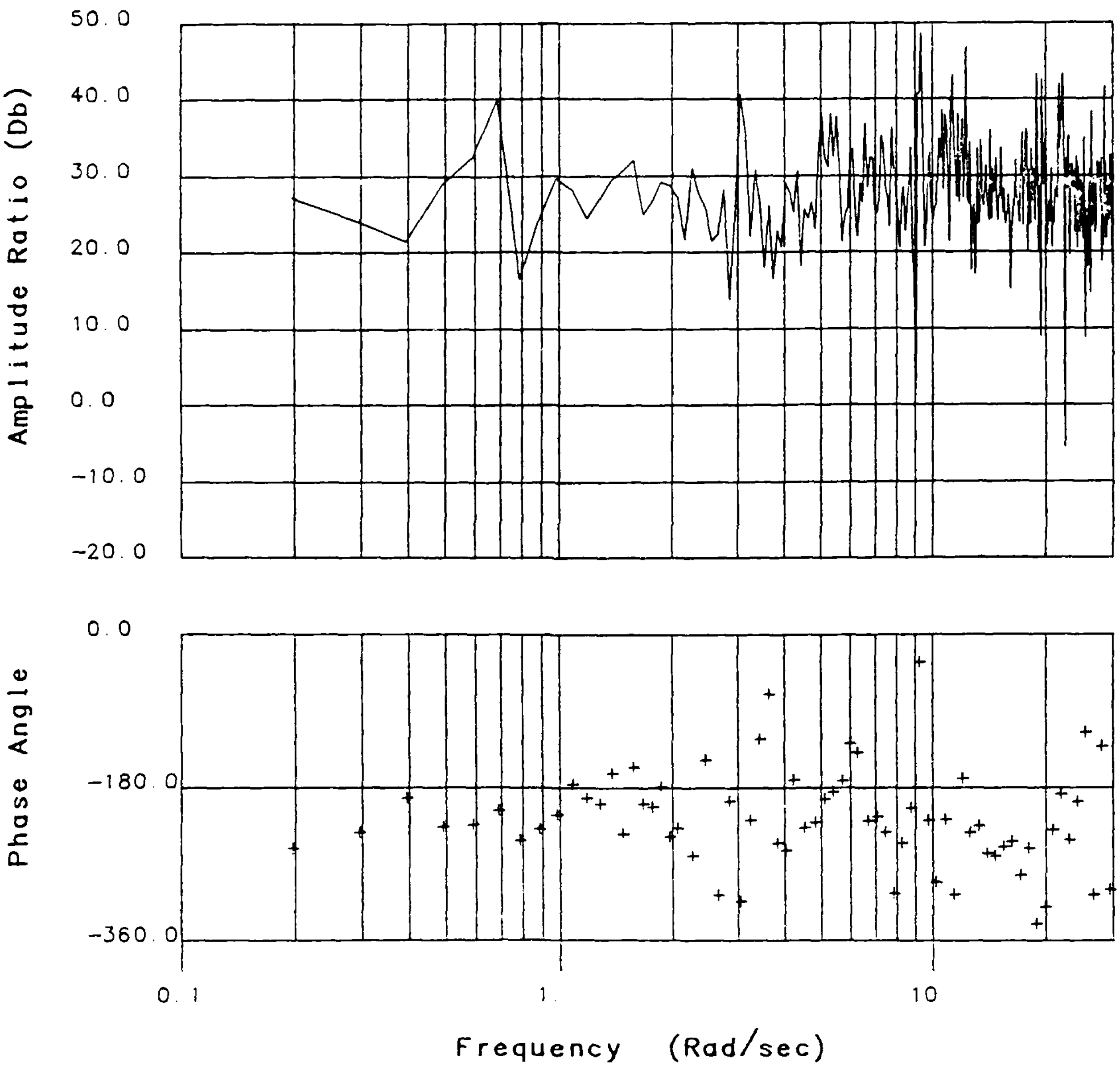

FIG. 12: BODE PLOT: FLIGHT DIRECTOR/DELTA c (40 KTS)

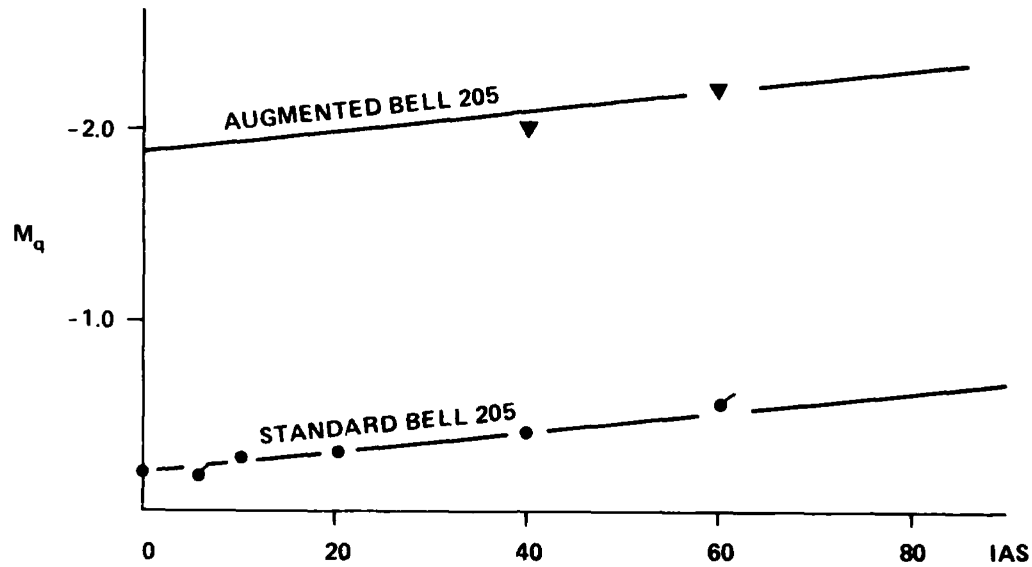

FIG. 13: BELL 205 M_q ESTIMATES

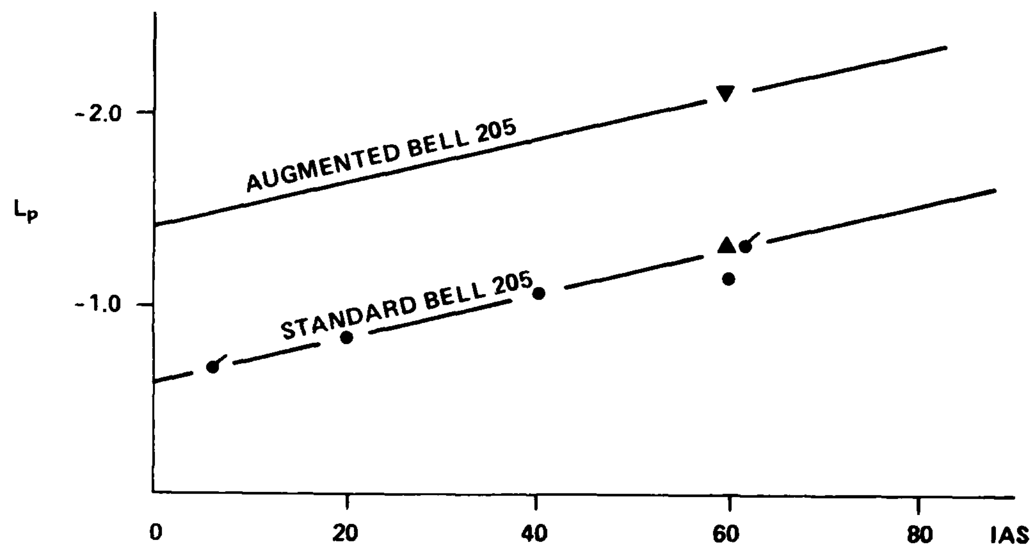

FIG. 14: BELL 205 L_p ESTIMATES

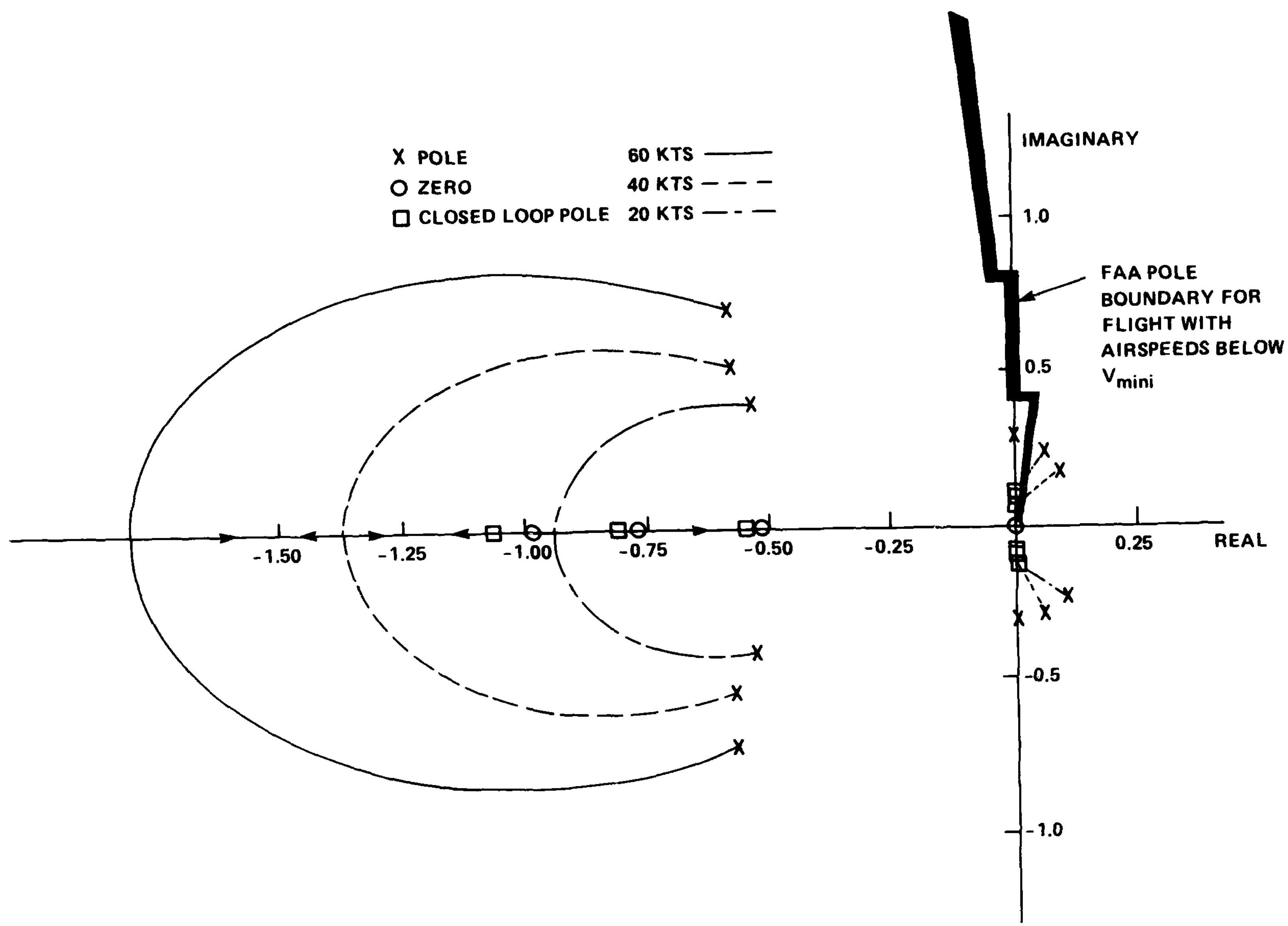

FIG. 15: LONGITUDINAL CLOSED LOOP POLES WITH M_q AUGMENTATION

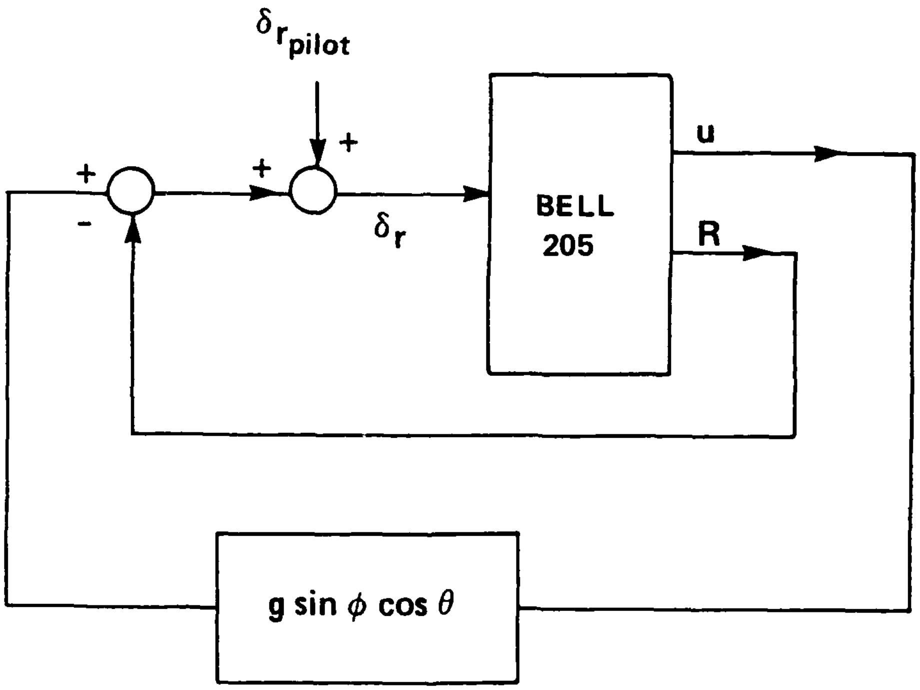

FIG. 16: TURN CO-ORDINATION CONTROL SYSTEM ARCHITECTURE

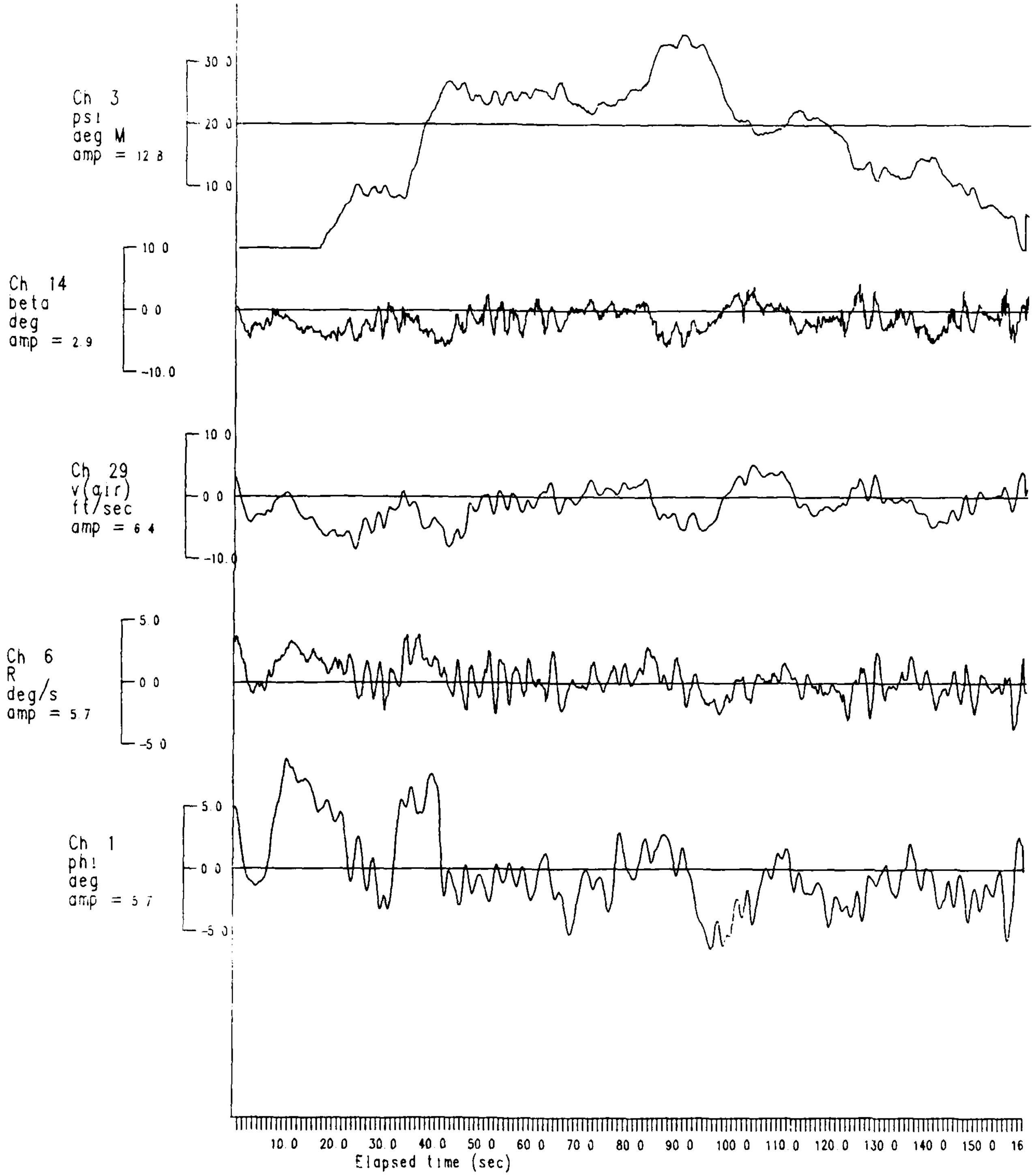

FIG. 17: TURN CO-ORDINATION PERFORMANCE

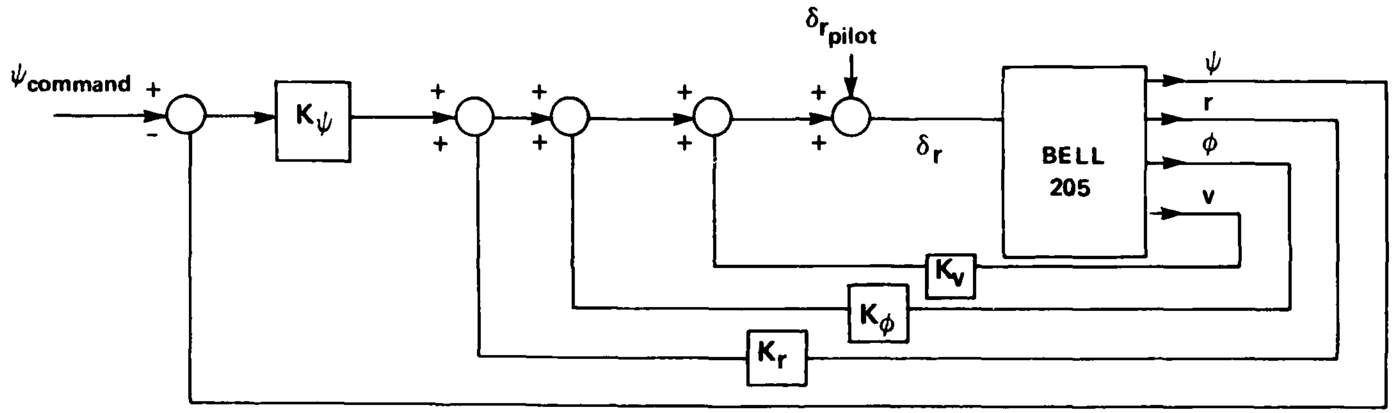

FIG. 18: HEADING HOLD CONTROL SYSTEM ARCHITECTURE

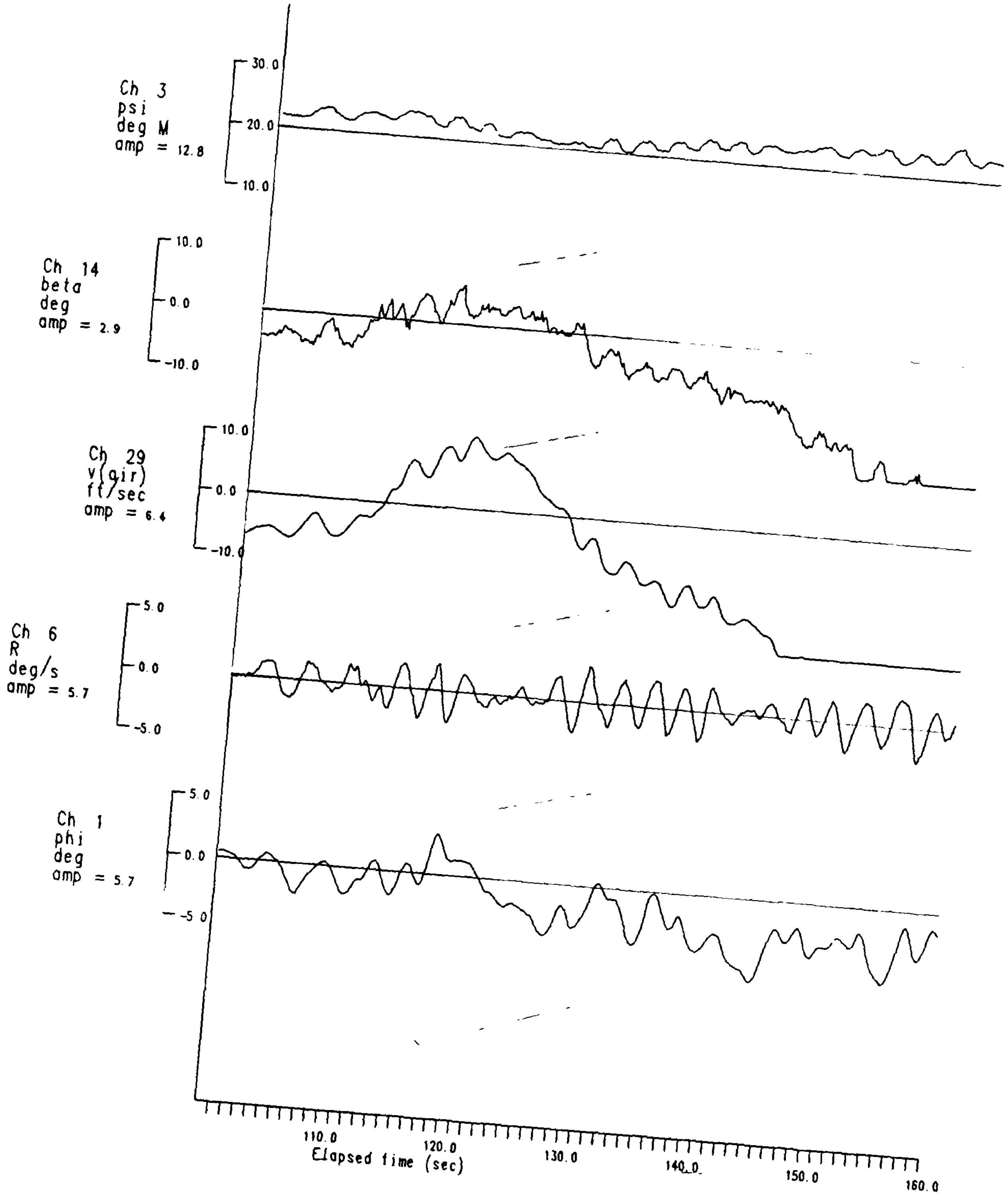

FIG. 19: HEADING HOLD PERFORMANCE

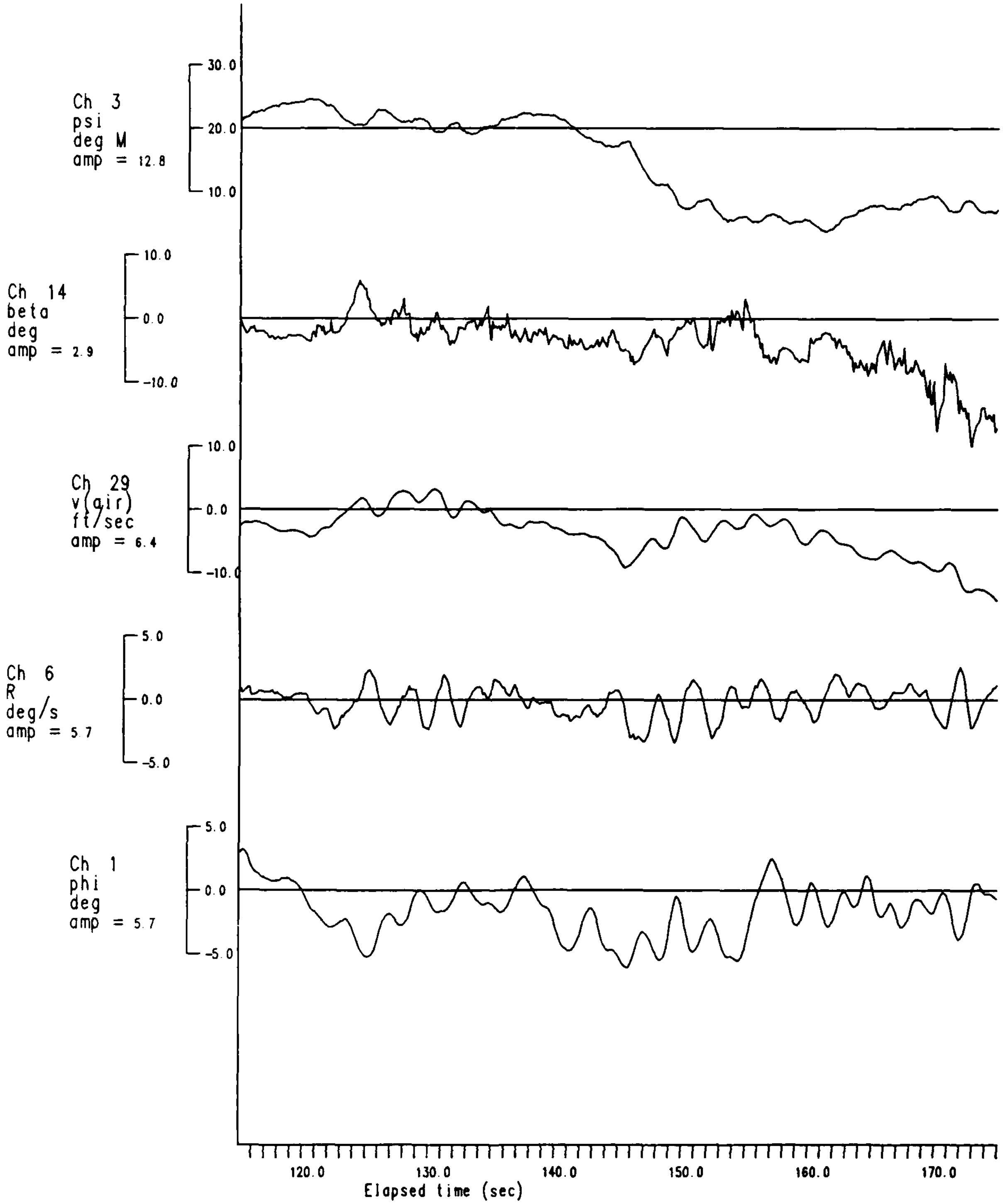

FIG. 20: TURN CO-ORDINATION/HEADING HOLD
BLEND PERFORMANCE EXAMPLE

PILOT	TOTAL FLIGHT TIME	TOTAL HELICOPTER	TOTAL INSTRUMENT
A	3200	2700	400
B	7800	1200	800
C	6000	4500	200
D	3000	2500	400
E	11000	8500	600

FIG. 21: EVALUATOR EXPERIENCE

EVALUATION PILOT ____________________ CONFIGURATION NO. ____________________

FLIGHT NO. ____________________ DECEL. YES ____________________

NO ______ SPEED ____________

AMBIENT WINDS & TURB ____

1. COMMENTS ON DISTINGUISHING FEATURES OR CHARACTERISTICS:

	PRIOR TO DECEL.	DURING DECEL.
i) AZIMUTH CONTROL		
ii) HEIGHT CONTROL		
iii) SPEED CONTROL		
iv) GENERAL COMMENTS		

2. COOPER/HARPER RATING OF MOST DIFFICULT PHASE ____________________

3. IFR CERTIFICATION LEVEL:

   GOOD SINGLE-PILOT ____________________

   MARGINAL SINGLE-PILOT ____________________

   TWO PILOT ____________________

   UNCERTIFIABLE ____________________

4. WORKLOAD RATING (MCH) ____________________

5. SIDEFORCE CHARACTERISTICS (OUT OF TRIM)

   NOT NOTICED ____________________

   NOTICEABLE ____________________

   OBJECTIONABLE ____________________

FIG. 22: HIFR QUESTIONNAIRE

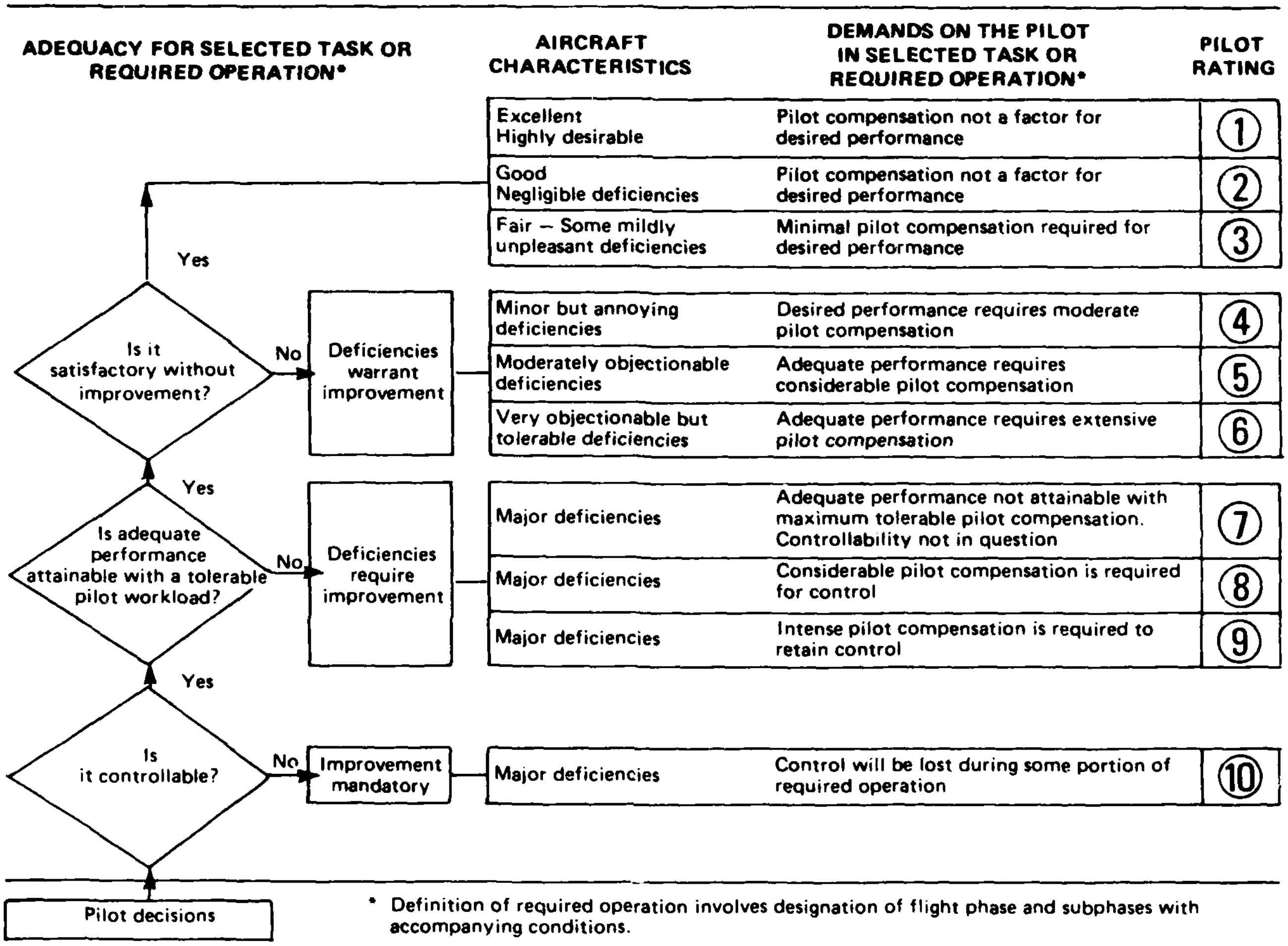

FIG. 23: HANDLING QUALITIES RATING SCALE

BASED ON YOUR SHORT EVALUATION, IN WHICH OF THE FOLLOWING CATEGORIES WOULD YOU PLACE THIS CONFIGURATION:

1. The helicopter has good flying qualities and could be operated safely in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

2. The helicopter has marginal flying qualities for operations in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

3. The helicopter has flying qualities deficiencies which make it unsuitable for single-pilot operations in a high-density IFR environment, however it could be operated safely within such an environment if the pilot-in-command were relieved of all non-control tasks by an additional qualified crew member. ☐

4. The helicopter has major flying qualities deficiencies which make it unsuitable for operation within a high-density IFR environment. ☐

FIG. 24: CERTIFICATION RELATED ASSESSMENT

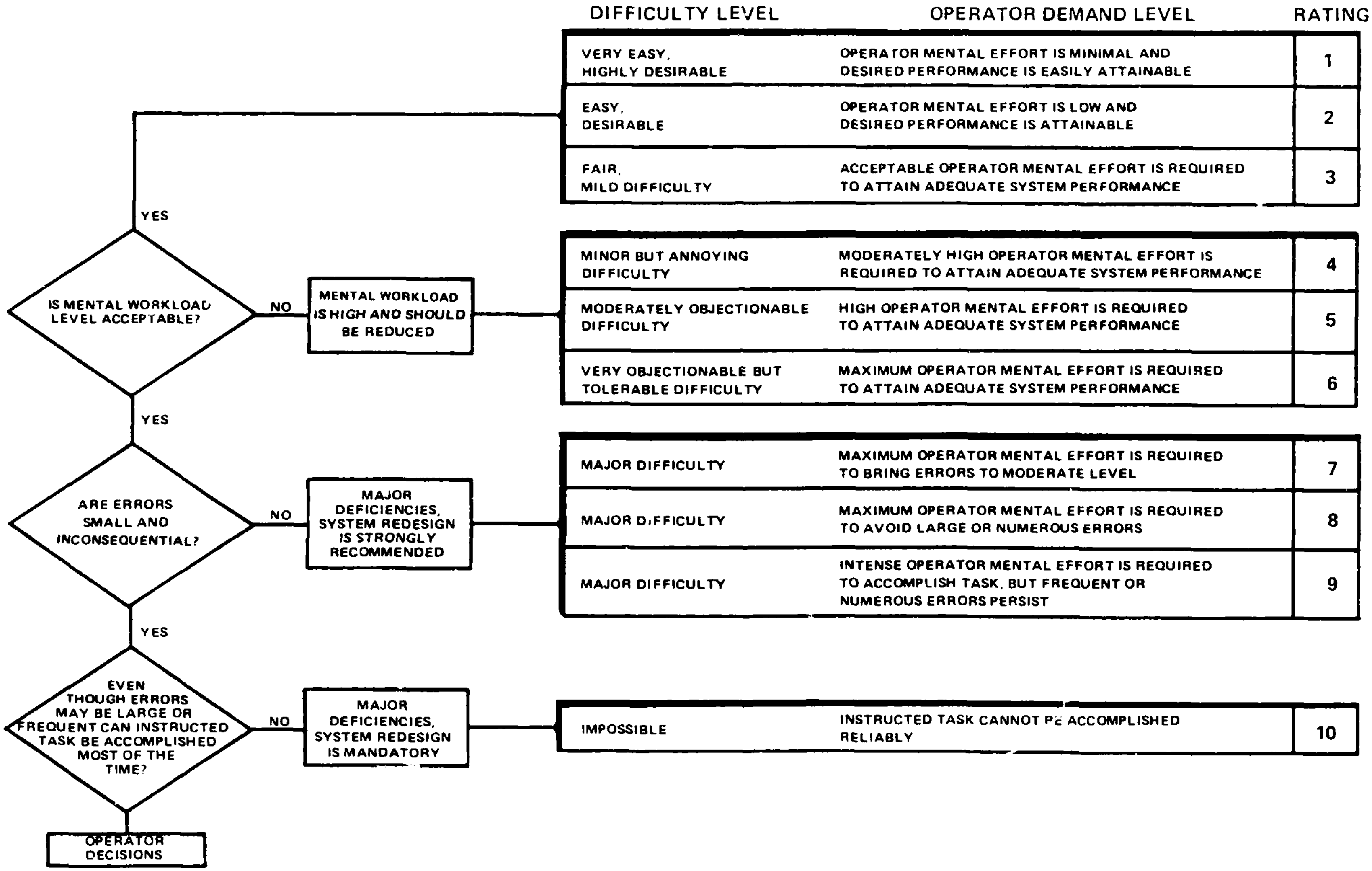

FIG. 25: MODIFIED COOPER/HARPER SCALE
(WORKLOAD RATING)

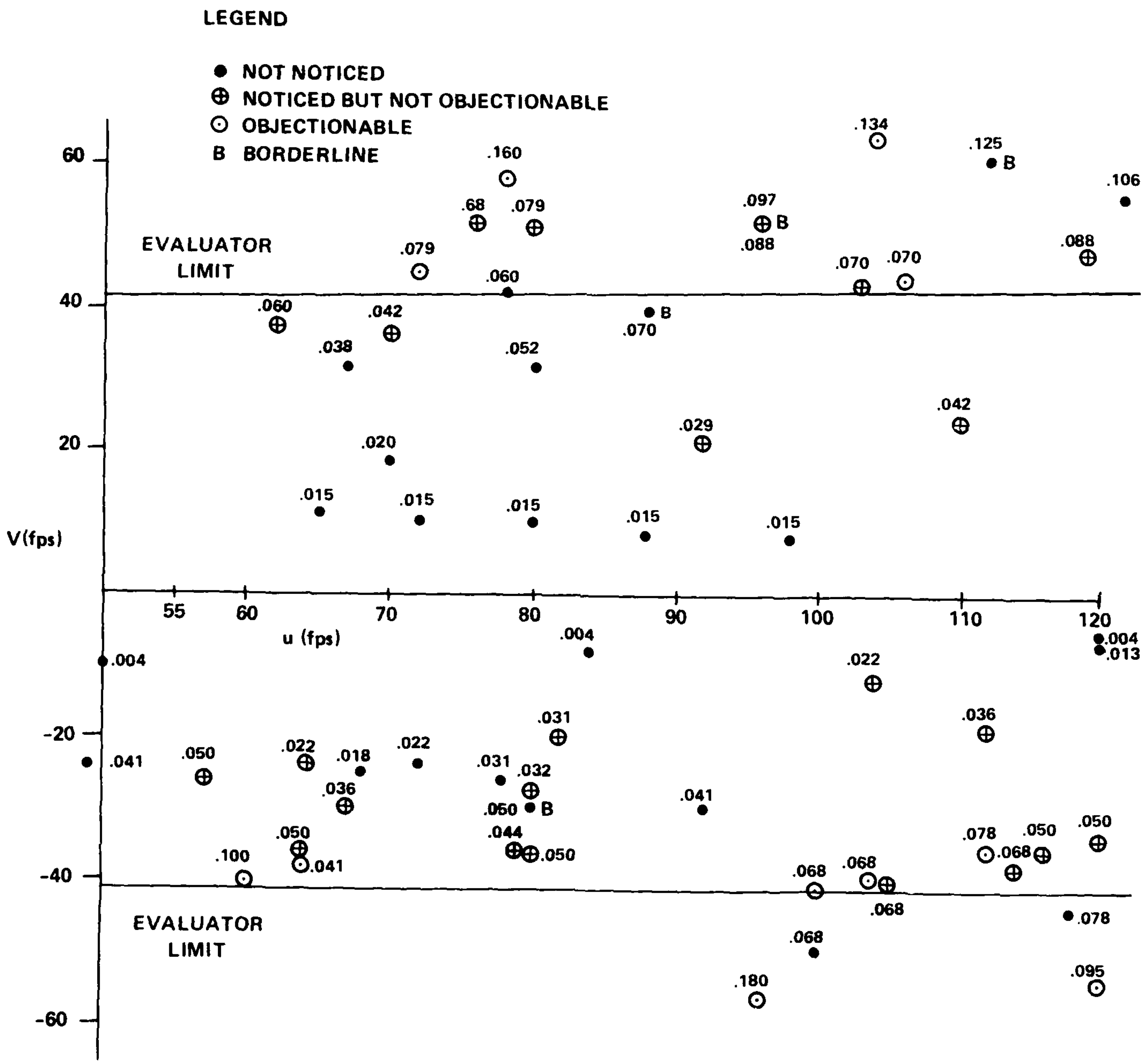

FIG. 26: LATERAL ACCELERATIONS ENCOUNTERED DURING SIDESLIP APPROACHES

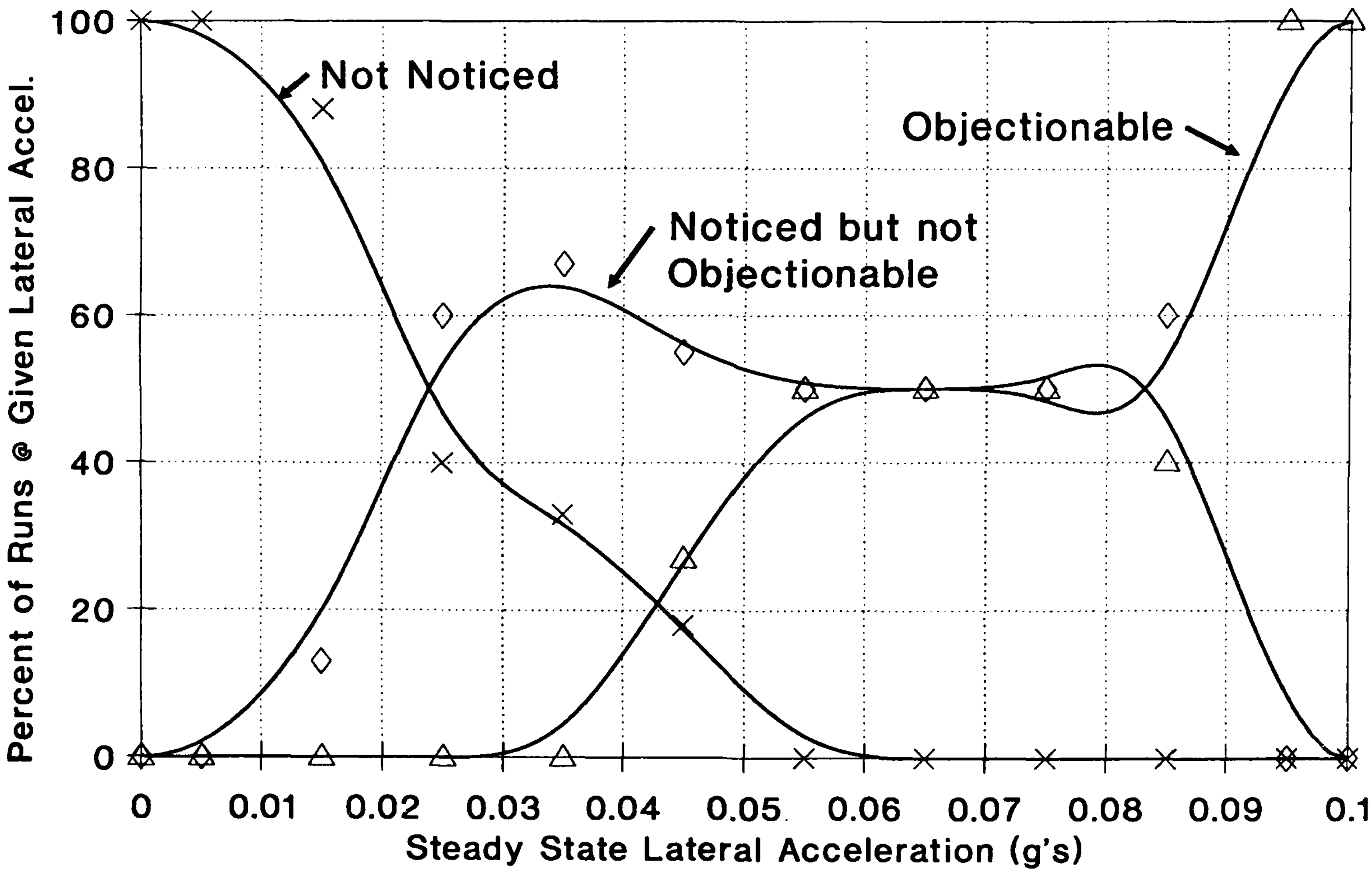

FIG. 27: SIDEFORCE SUBJECTIVE RATINGS

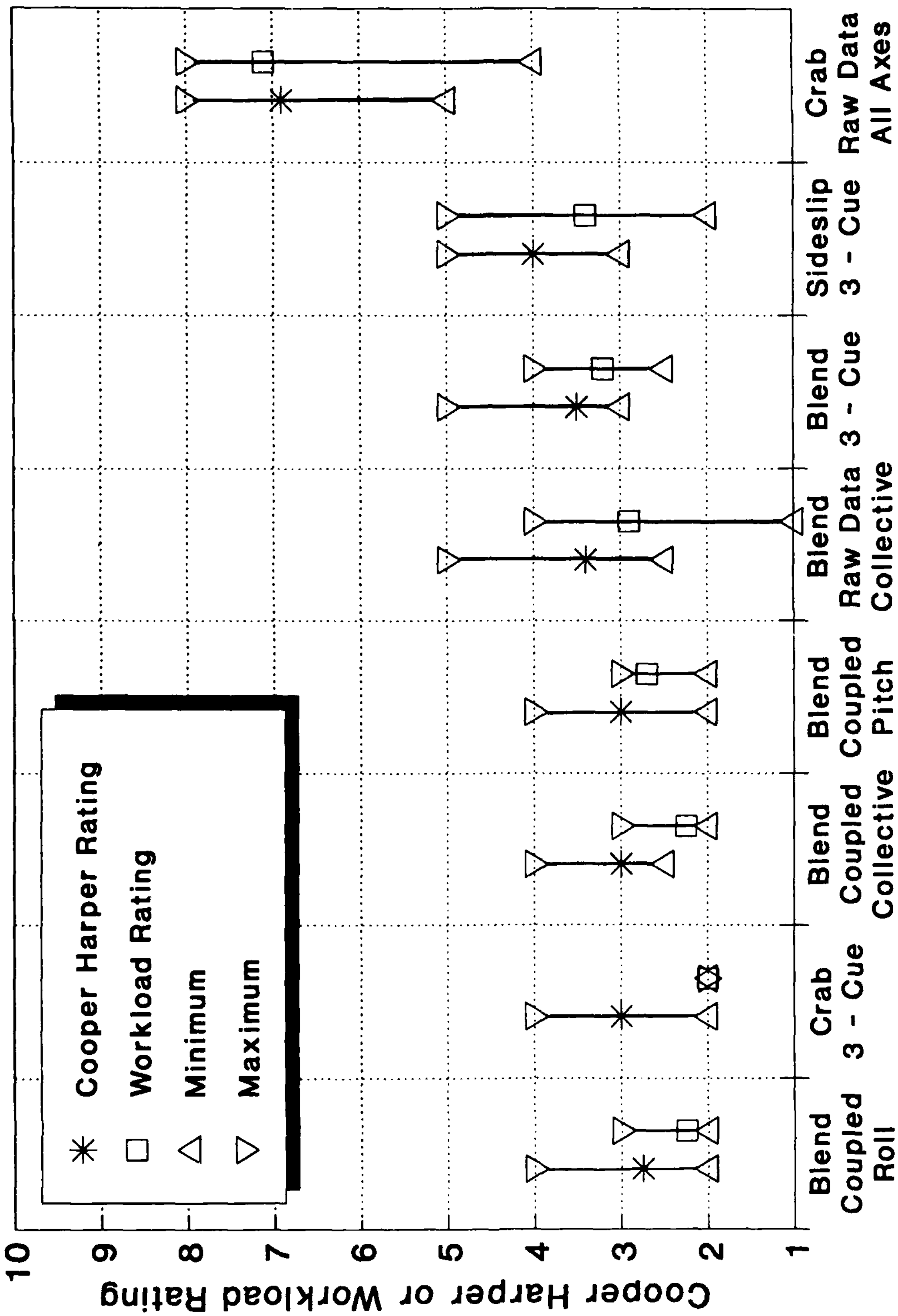

FIG. 28: DECELERATING APPROACH RATINGS

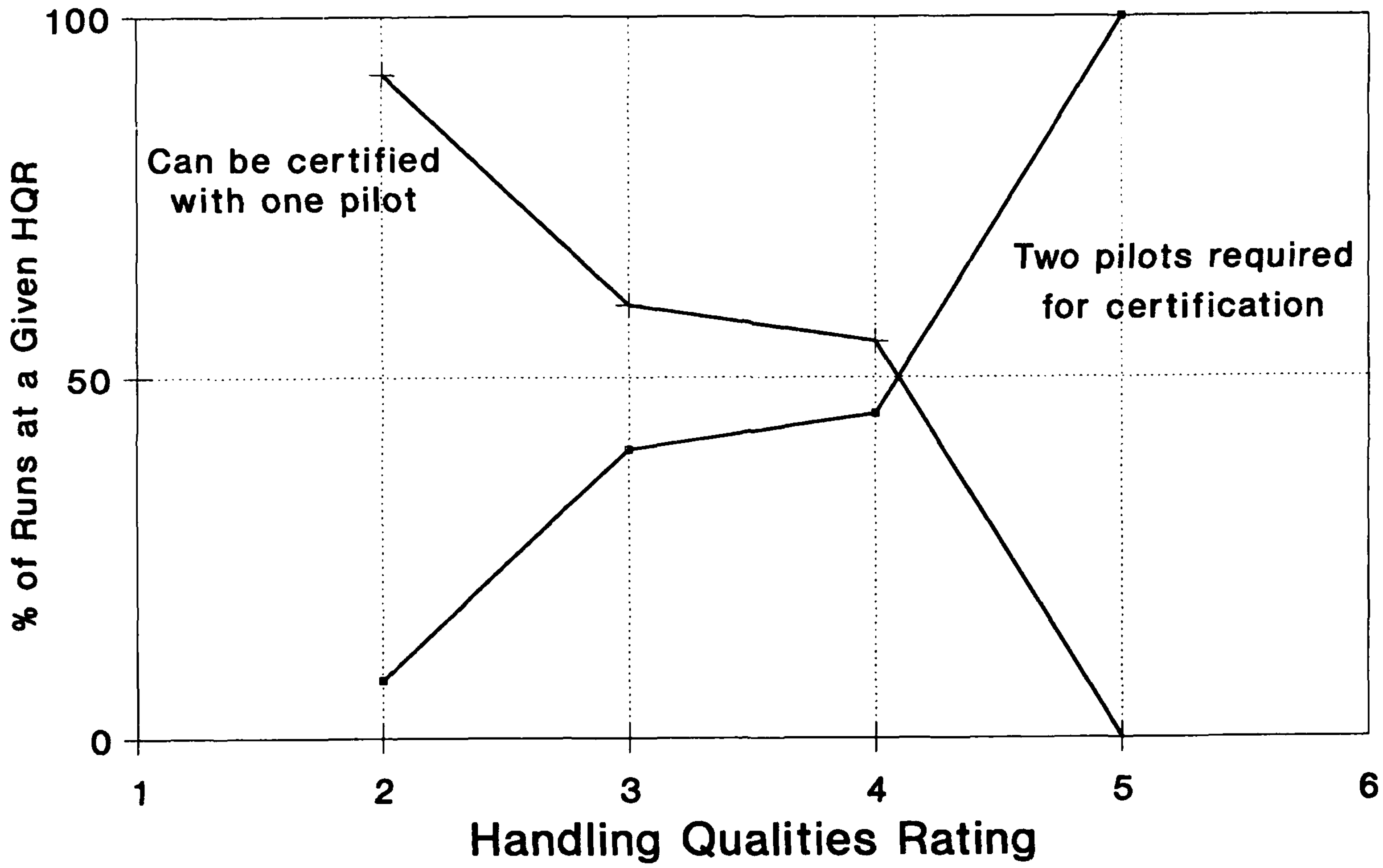

FIG. 29: ONE VERSUS TWO PILOT CERTIFICATION DATA

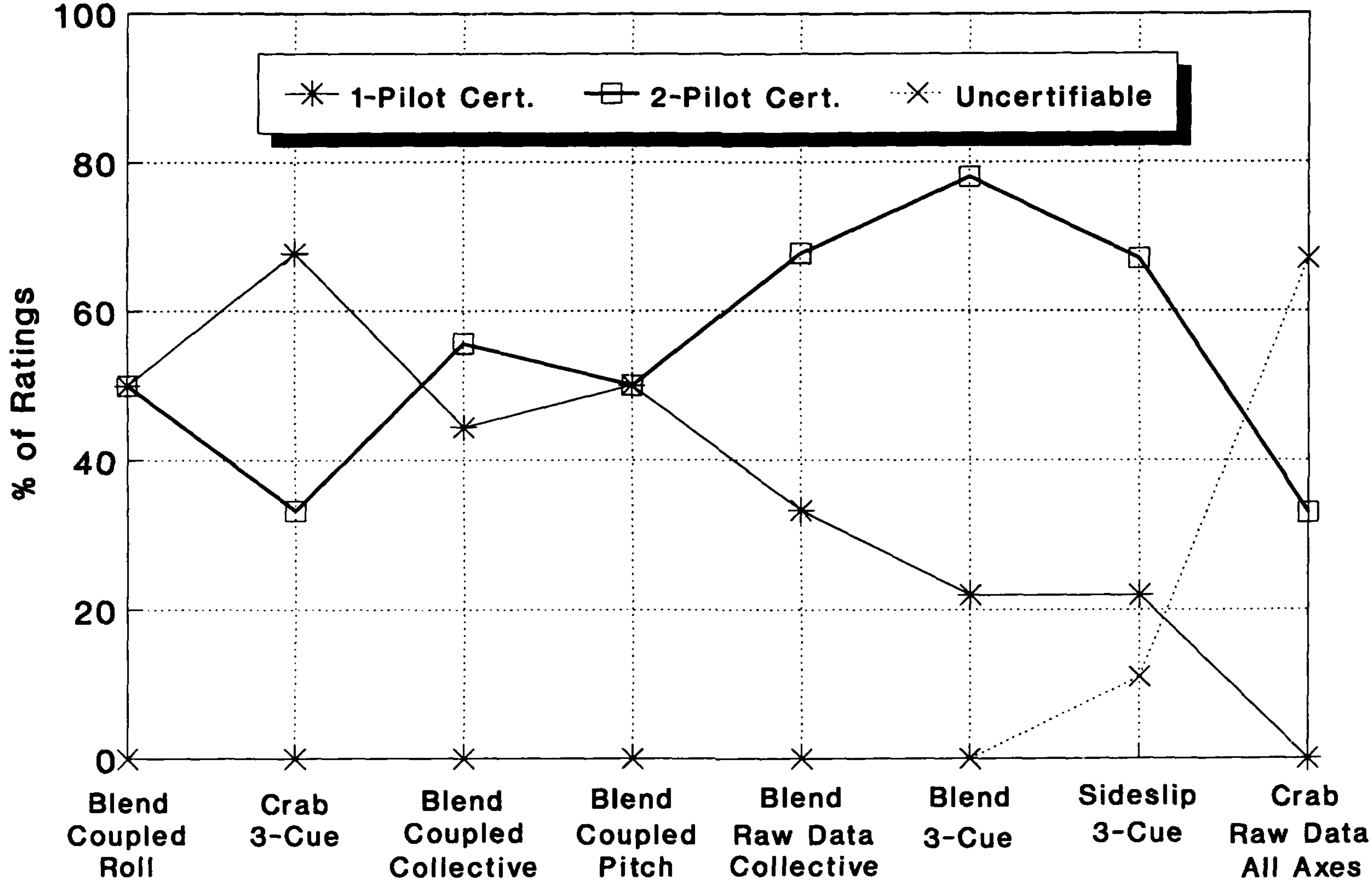

FIG. 30: CERTIFICATION ASSESSMENTS FOR DECELERATING APPROACHES

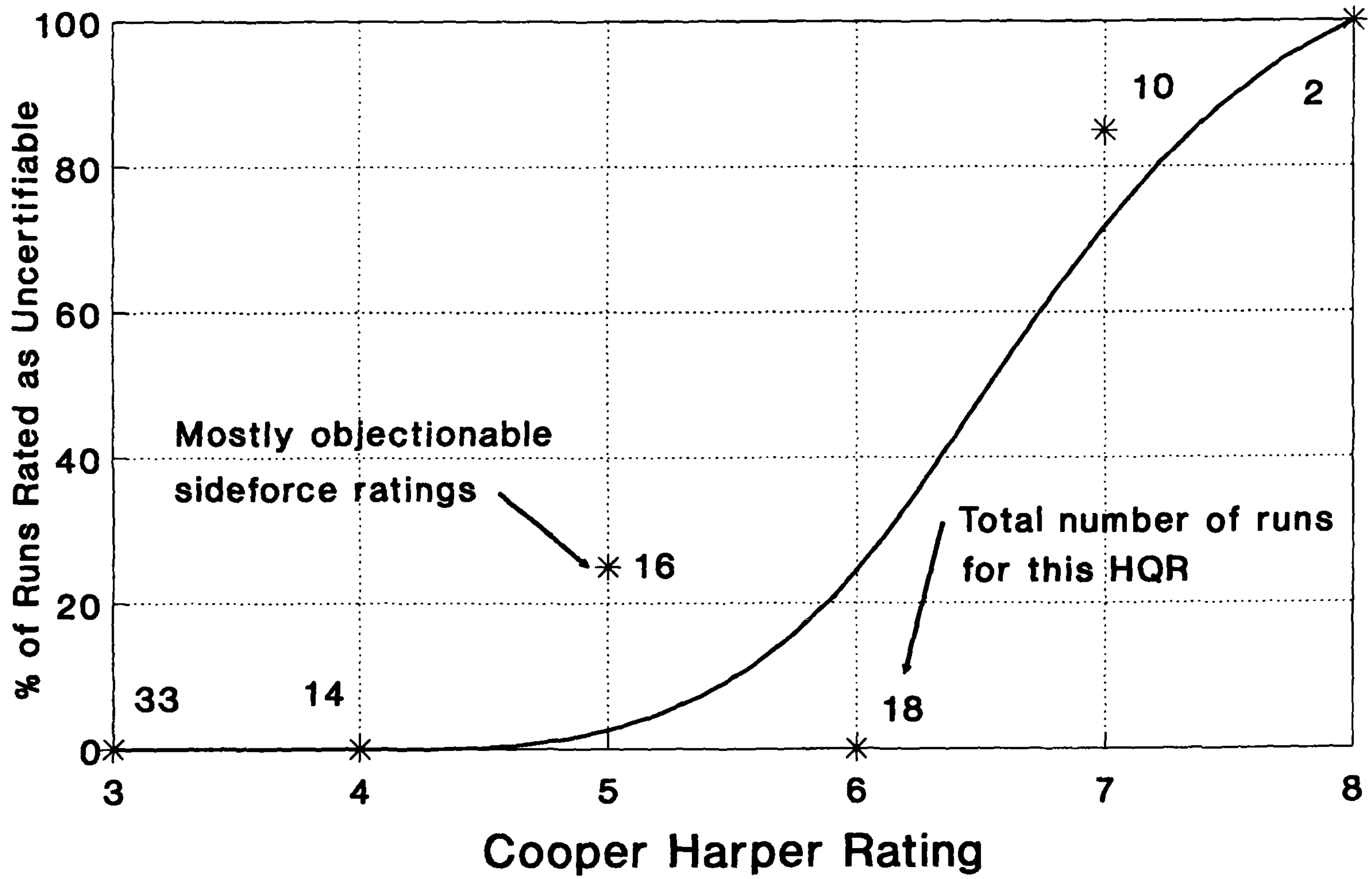

FIG. 31: EFFECT OF HQR ON UNCERTIFIABLE ASSESSMENTS

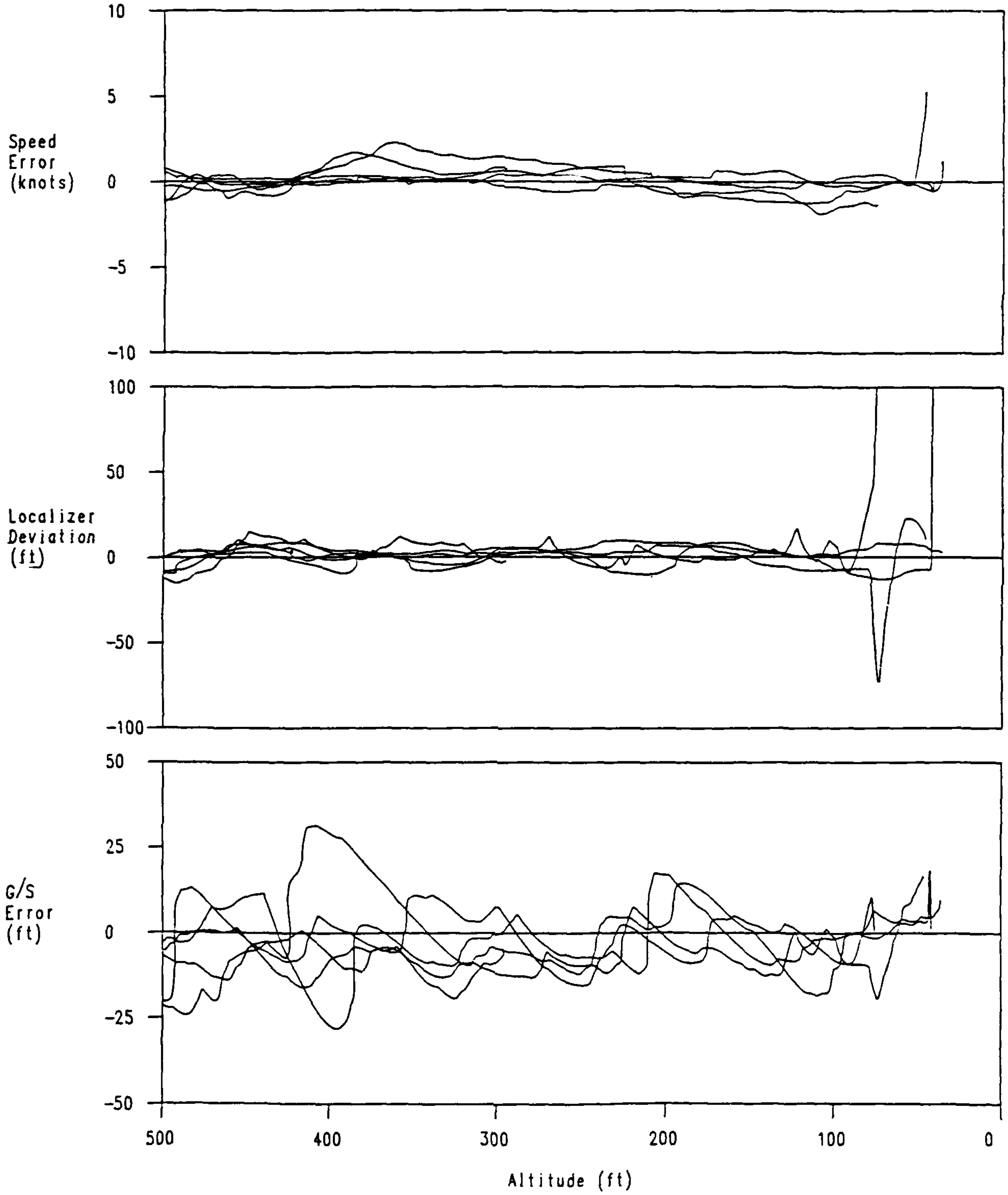

FIG. 32: CONSTANT SPEED – 30 KTS – CRAB TECHNIQUE

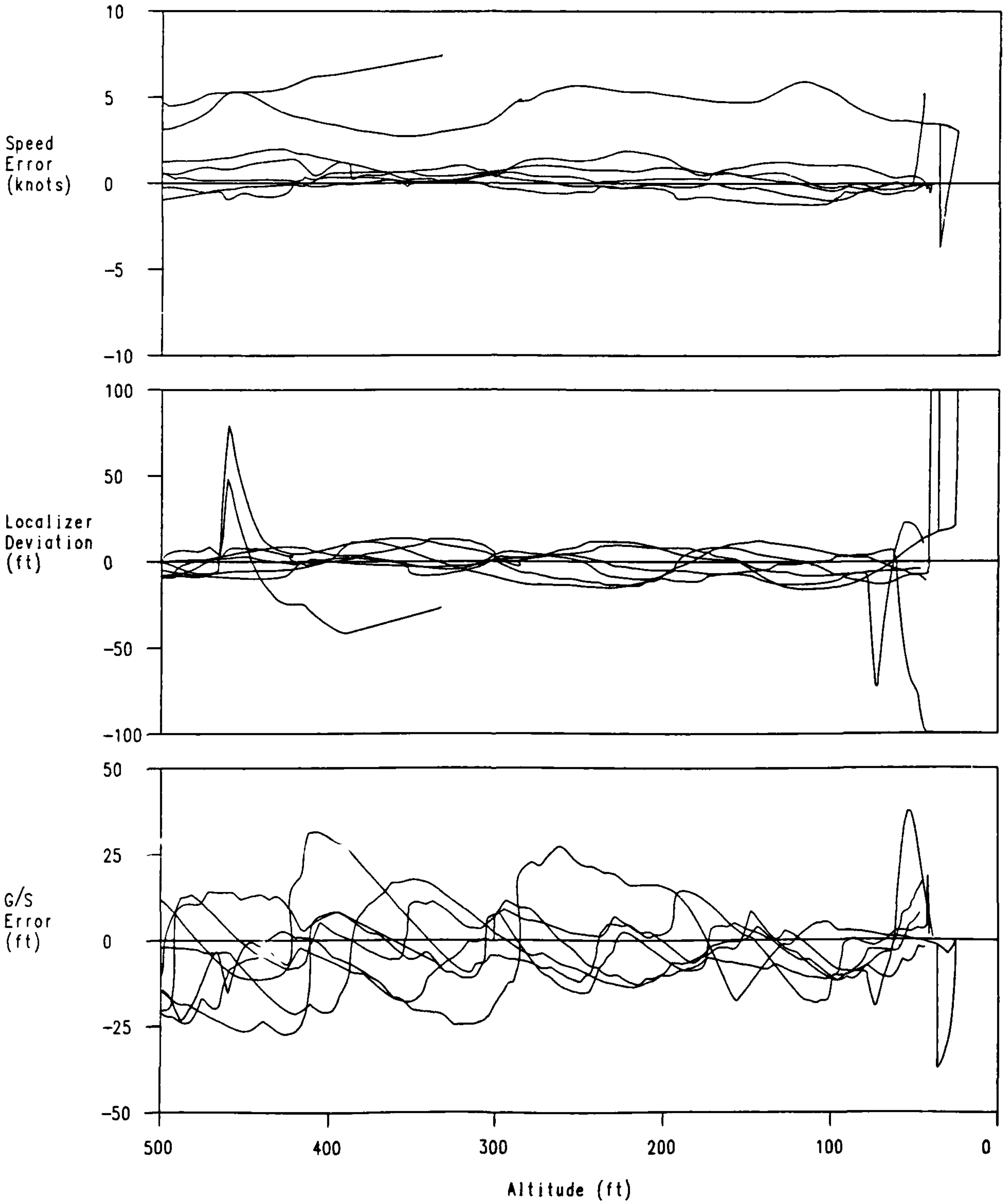

FIG. 33: CONSTANT SPEED – 40 KTS – CRAB TECHNIQUE

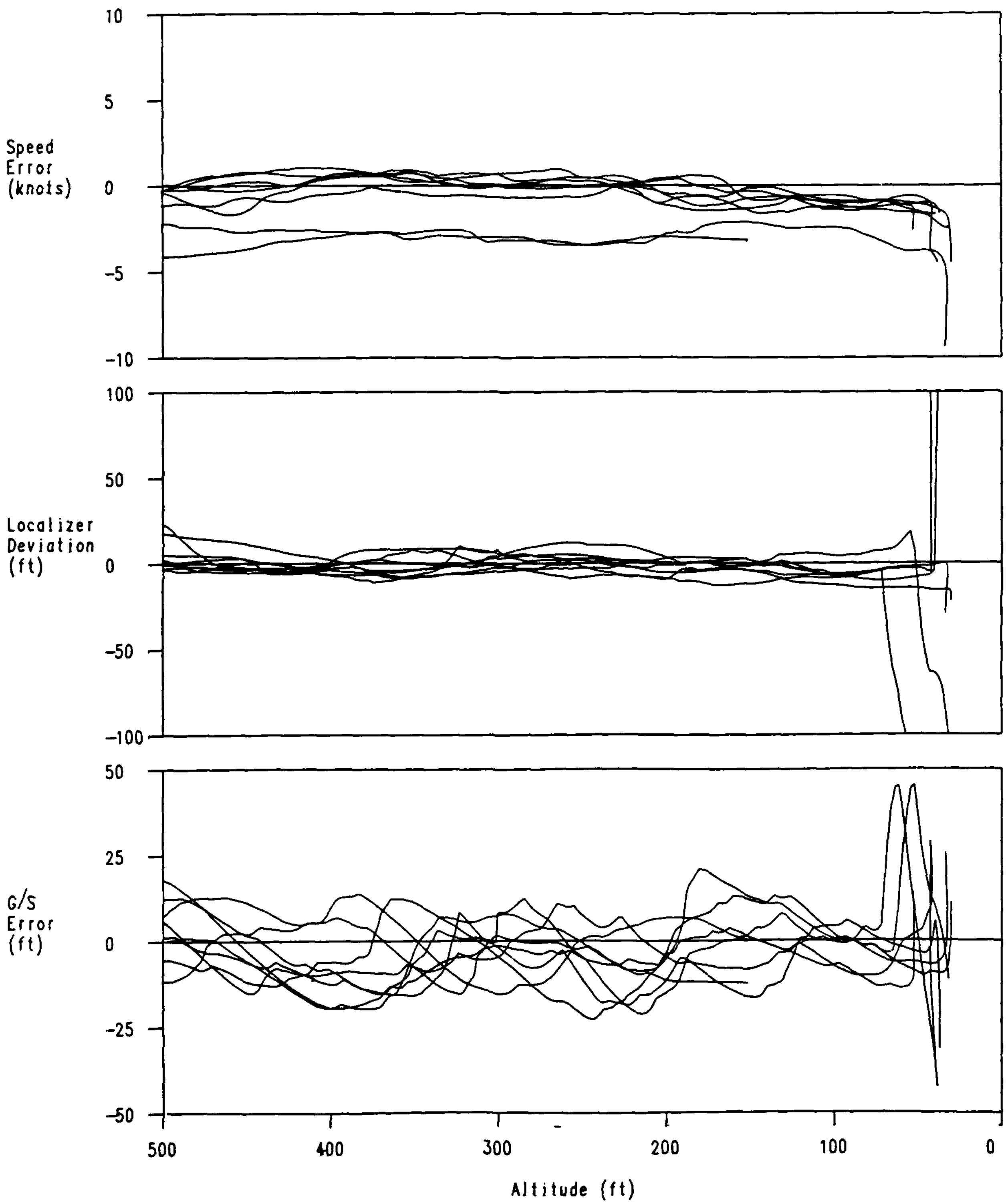

FIG. 34: CONSTANT SPEED – 50 KTS – CRAB TECHNIQUE

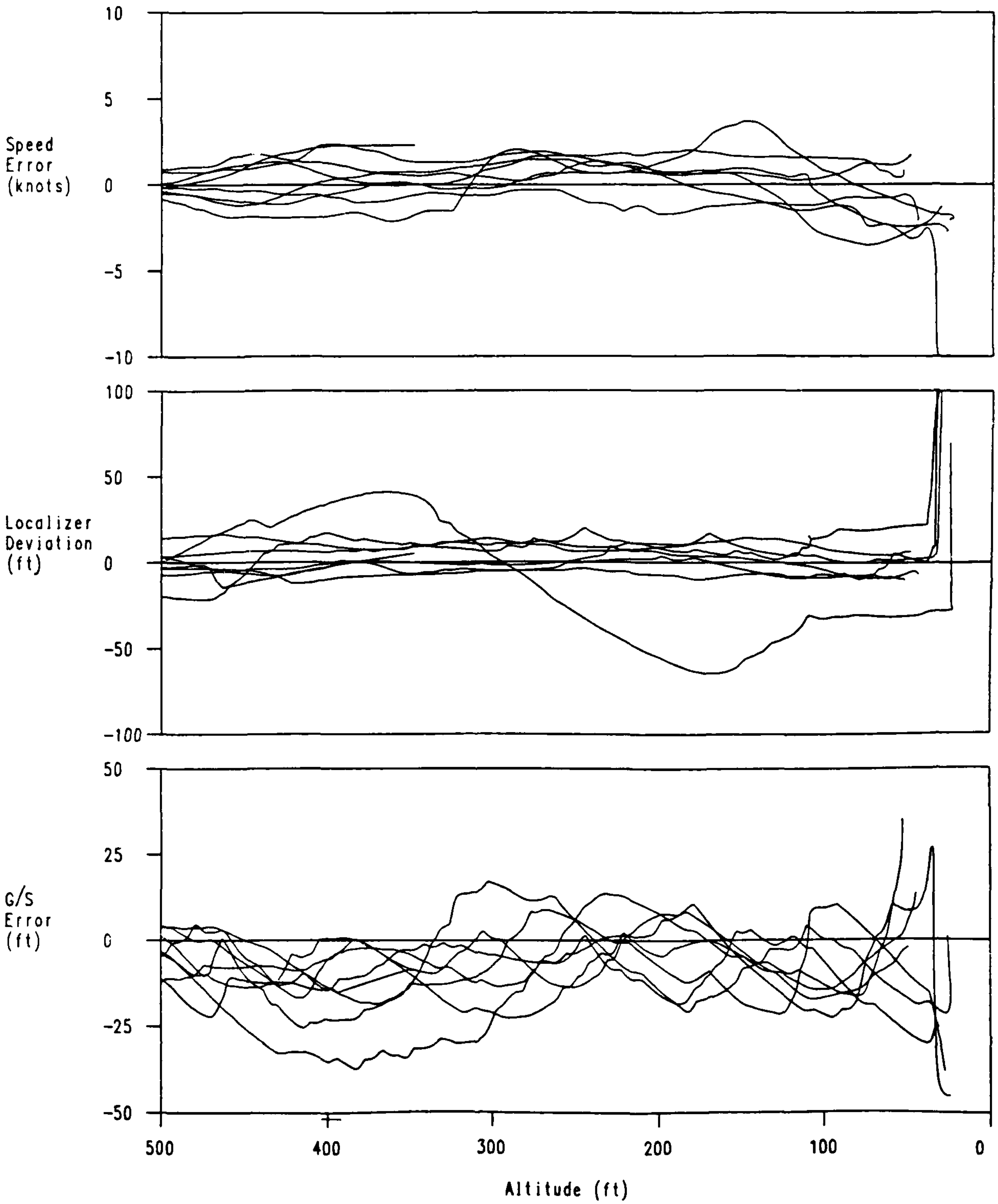

FIG. 35: CONSTANT SPEED — 50 KTS — SIDESLIP TECHNIQUE

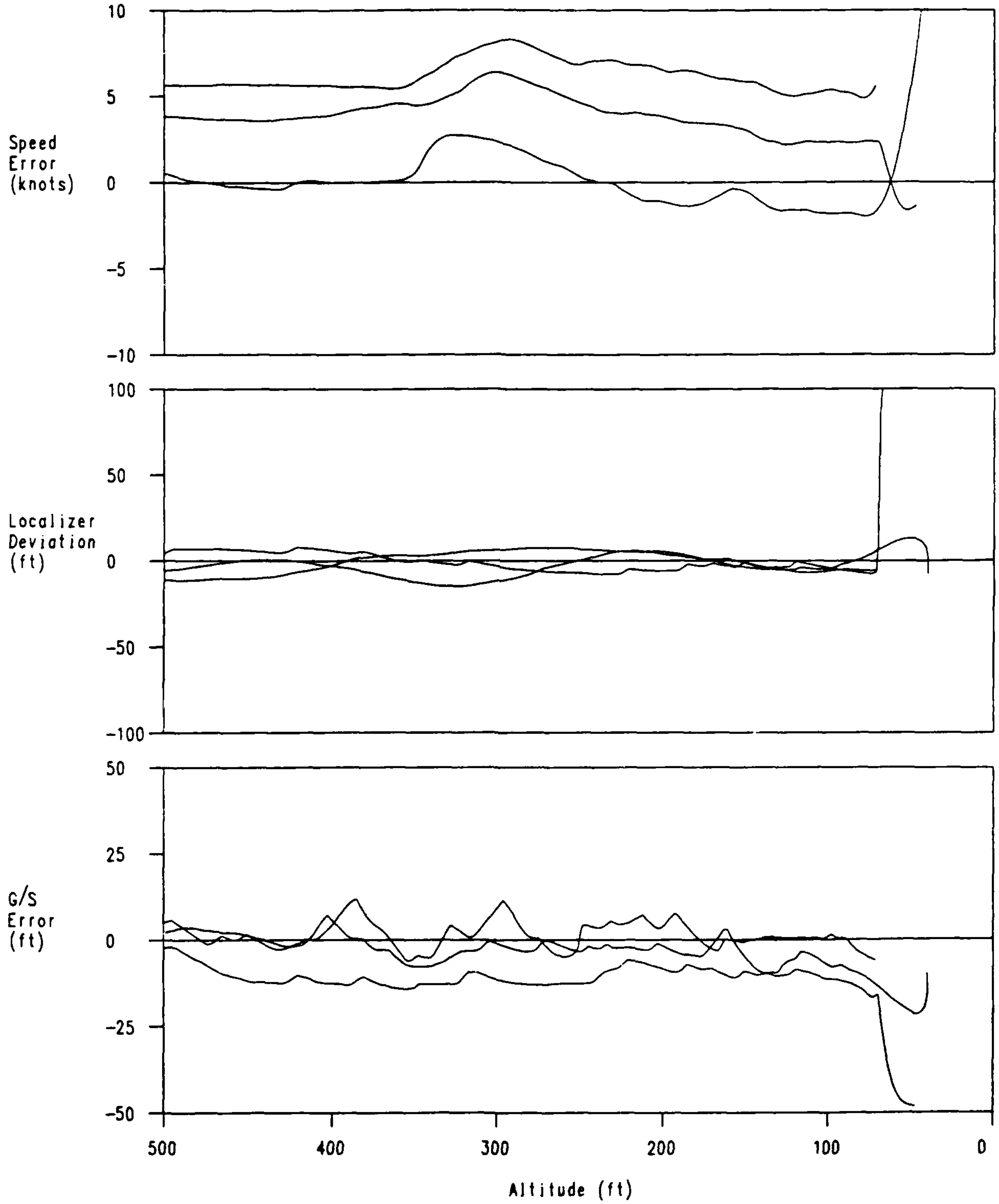

FIG. 36: DECELERATING APPROACHES – FULLY COUPLED

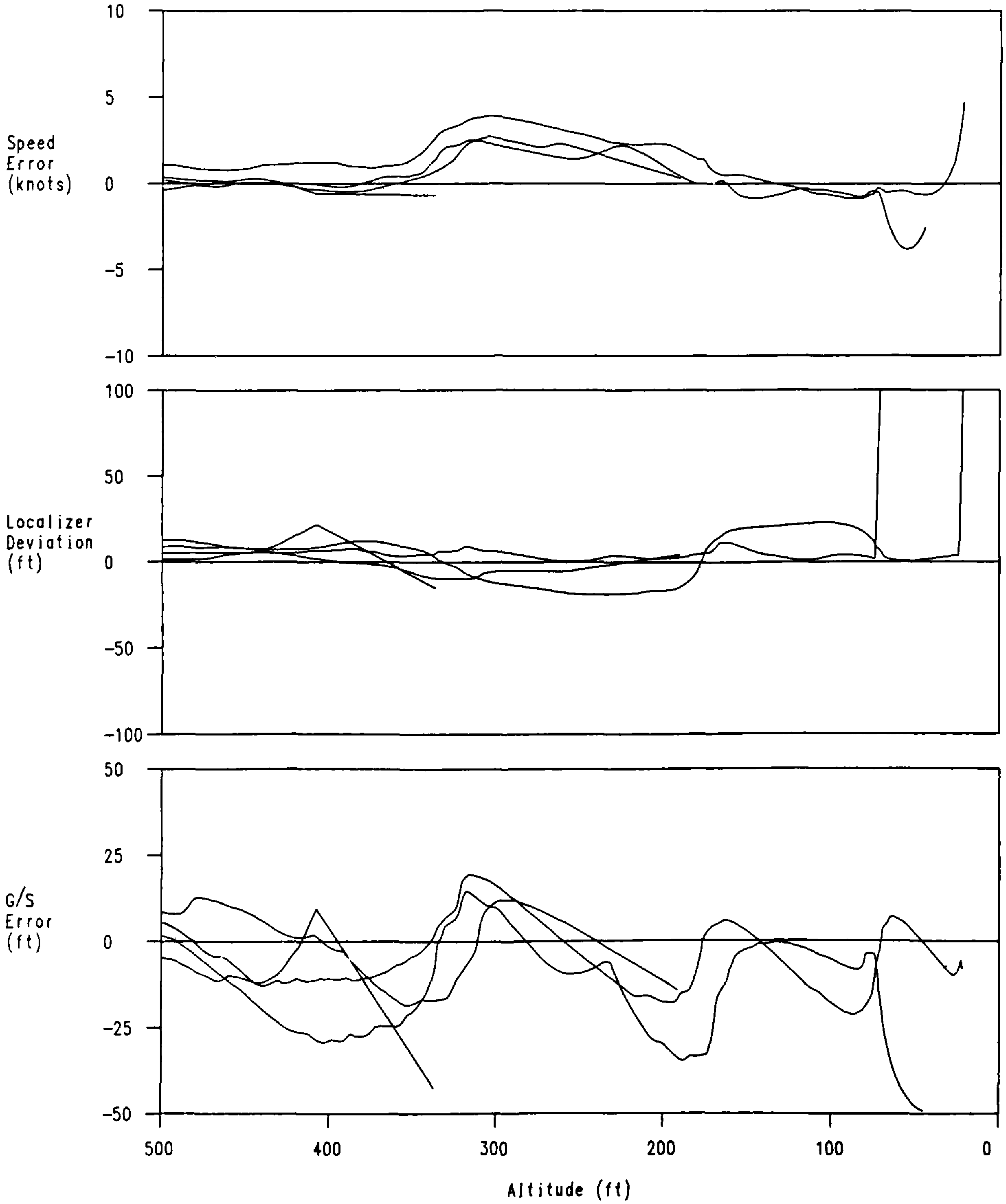

FIG. 37: DECELERATING APPROACHES — COUPLED PITCH

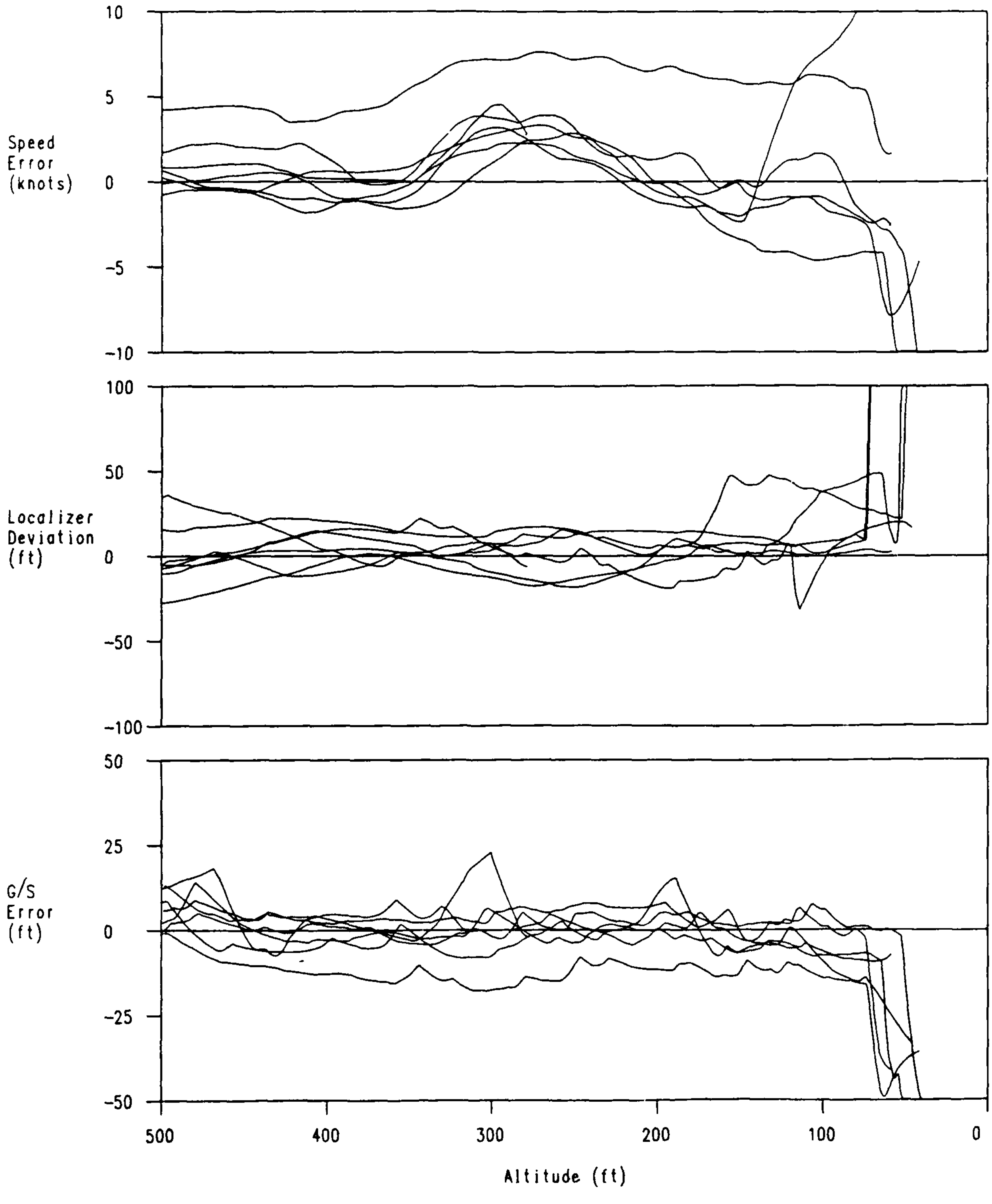

FIG. 38: DECELERATING APPROACHES – COUPLED COLLECTIVE

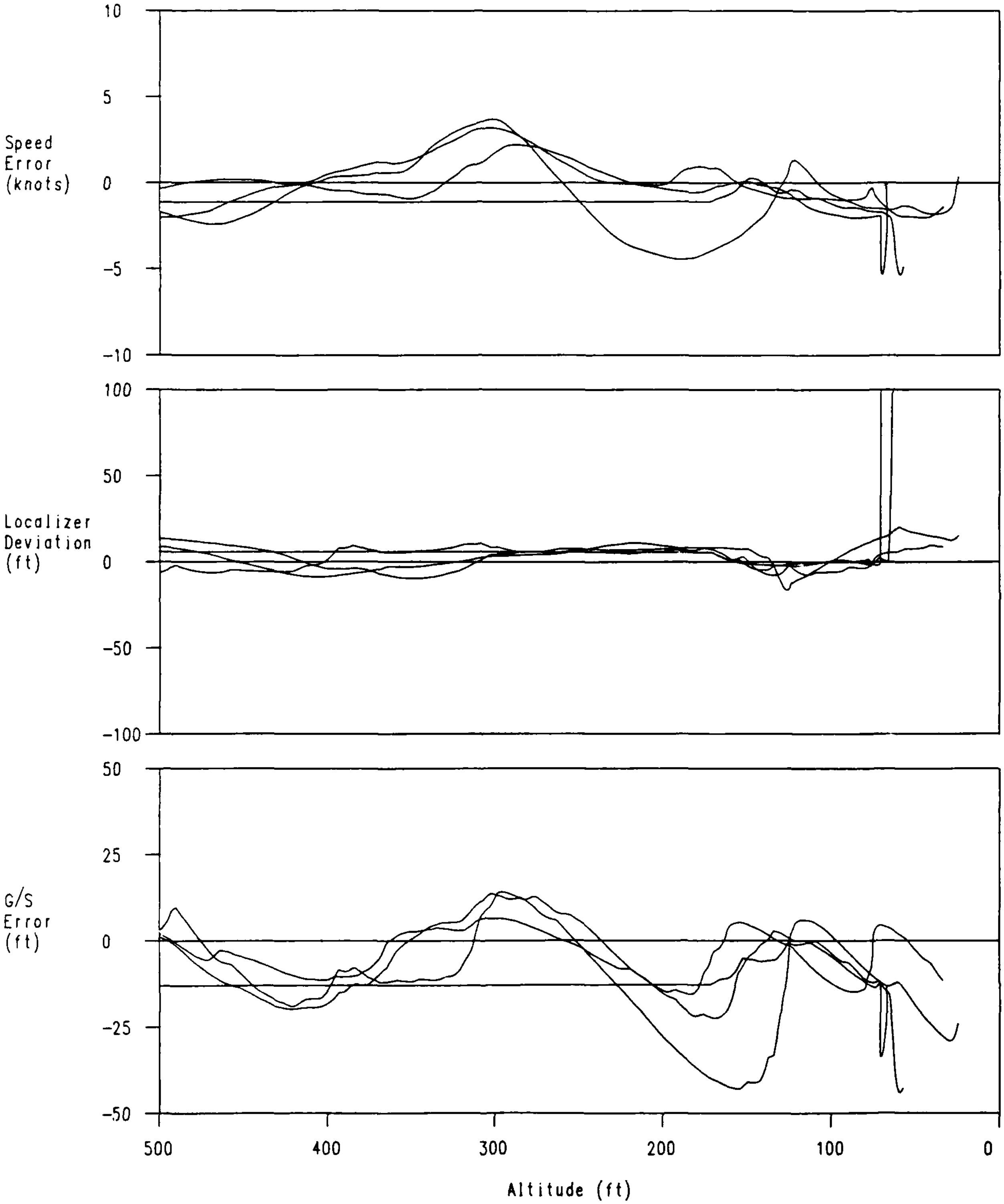

FIG. 39: DECELERATING APPROACHES – COUPLED ROLL

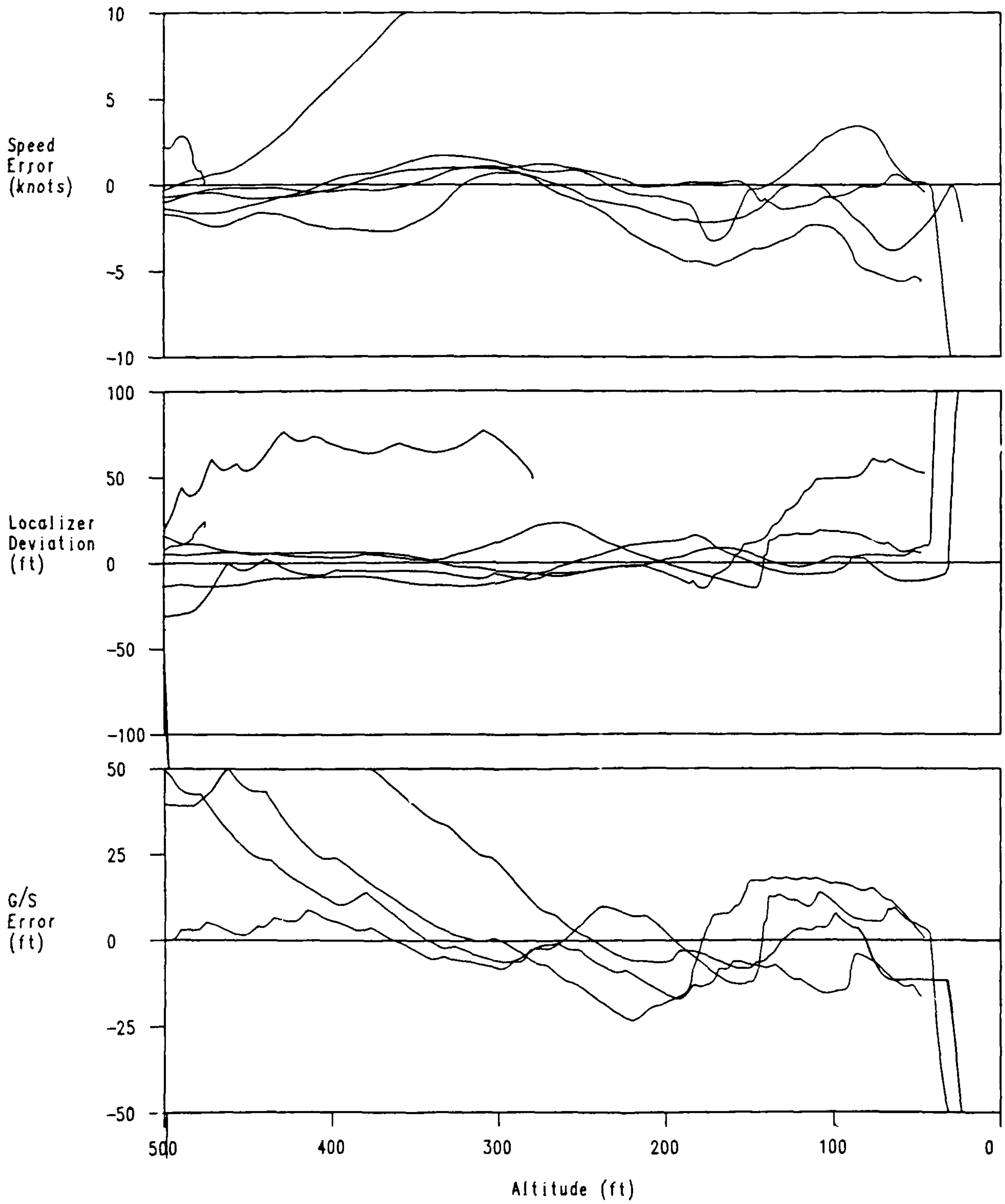

FIG. 40: DECELERATING APPROACHES — BLEND-RAW DATA COLLECTIVE

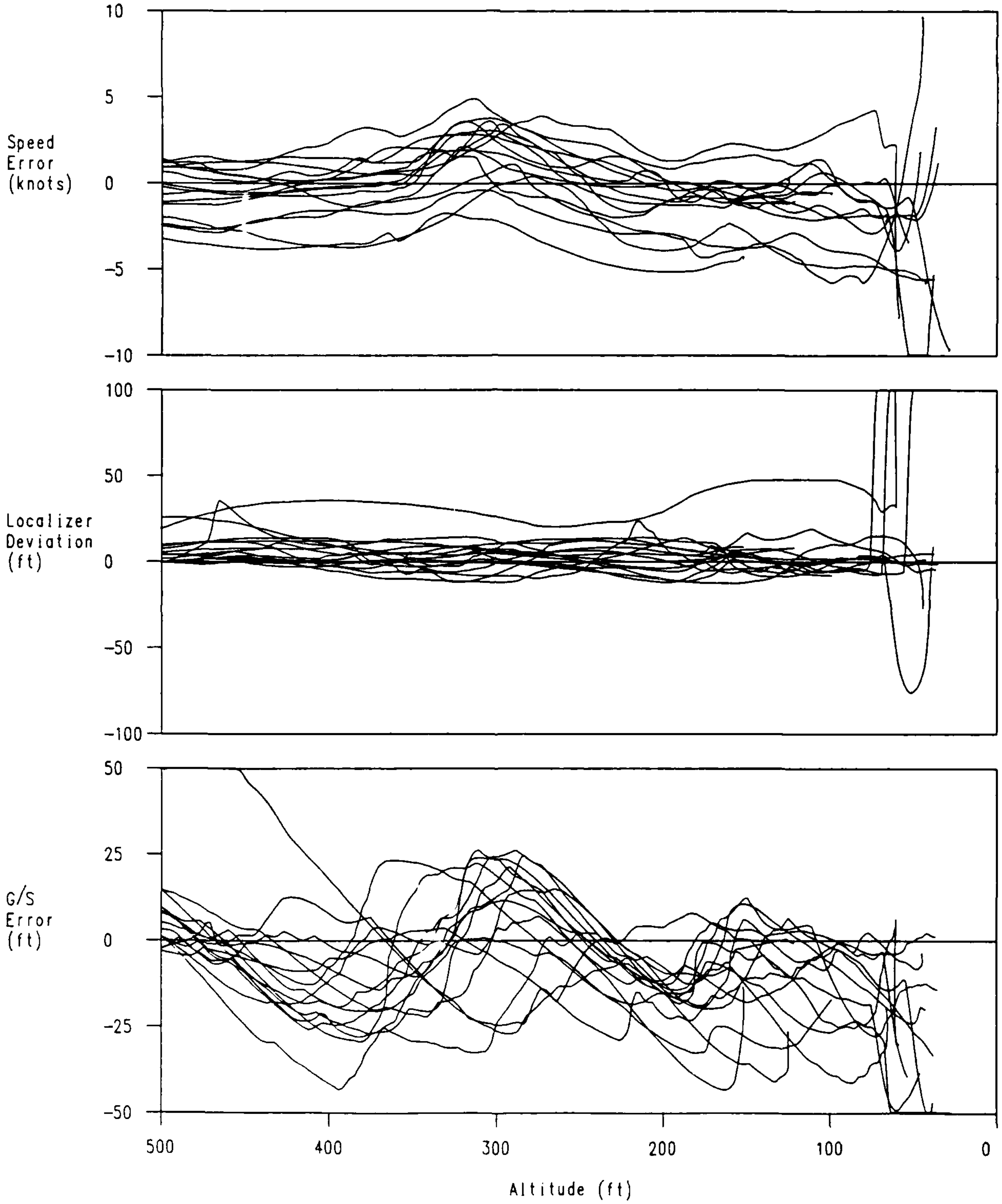

FIG. 41: DECELERATING APPROACHES – BLEND – 3 CUE

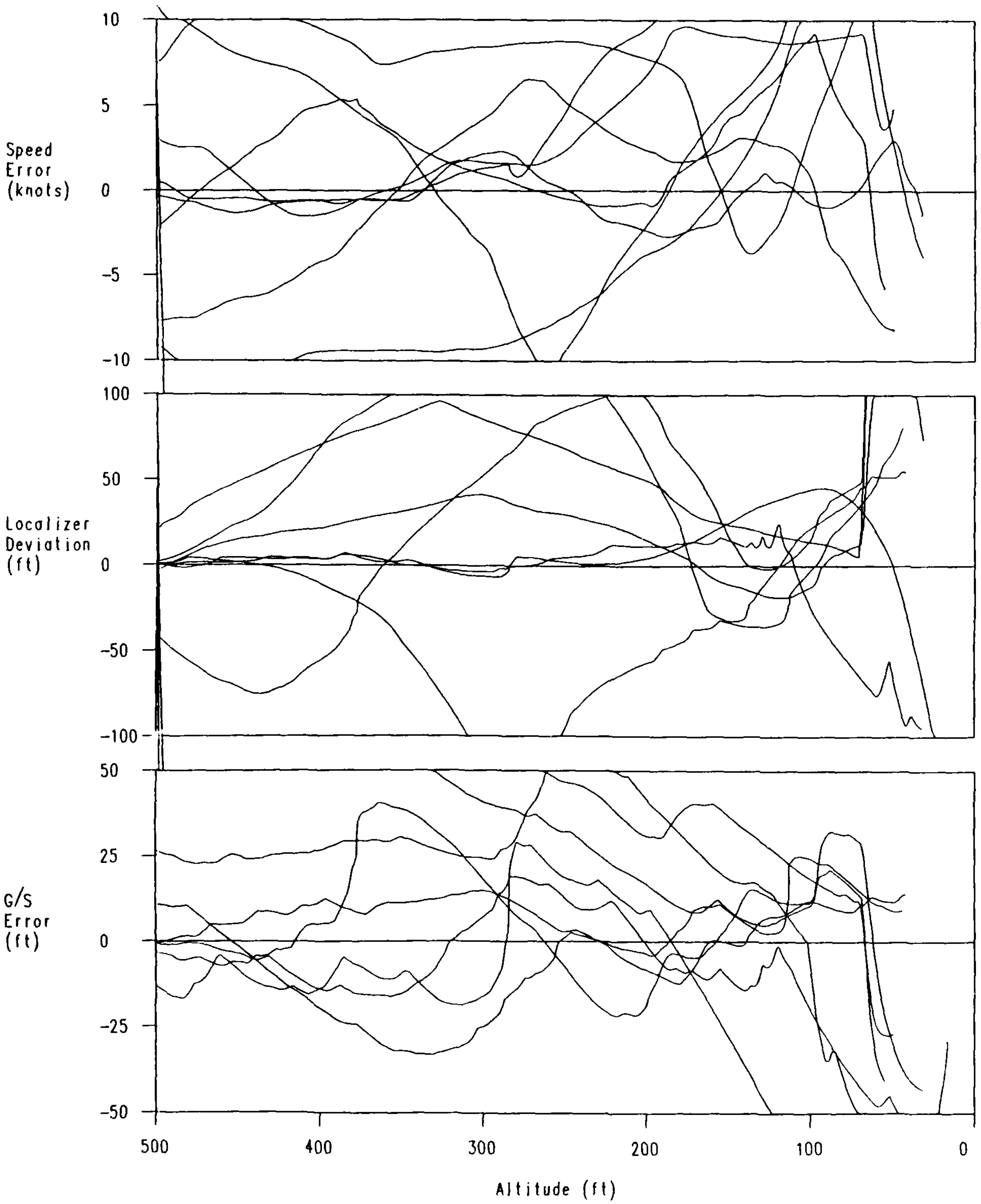

FIG. 42: DECELERATING APPROACHES – BLEND – RAW DATA

REPORT DOCUMENTATION PAGE / PAGE DE DOCUMENTATION DE RAPPORT

REPORT/RAPPORT	REPORT/RAPPORT
NAE-AN-55 (1a)	NRC No. 29604 (1b)
REPORT SECURITY CLASSIFICATION / CLASSIFICATION DE SÉCURITÉ DE RAPPORT: Unclassified (2)	DISTRIBUTION (LIMITATIONS): Unlimited (3)

TITLE/SUBTITLE/TITRE/SOUS-TITRE

4 An Investigation of Lateral Tracking Techniques, Flight Directors and Automatic Control Coupling on Decelerating IFR Approaches for Rotorcraft

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6 Aeronautical Note

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7 National Research Council Canada
National Aeronautical Establishment High Speed Aerodynamics Laboratory

SPONSORING AGENCY/AGENCE DE SUBVENTION

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DATE	FILE/DOSSIER	LAB. ORDER COMMANDE DU LAB.	PAGES	FIGS/DIAGRAMMES
88-10			72	42
9	10	11	12a	12b

NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Wind profiles
2. Velocity distribution

14

SUMMARY/SOMMAIRE

An in flight simulation experiment was performed to investigate the impact on handling qualities and certification of various issues associated with low minima decelerating flight directed IFR approaches for rotorcraft. These issues were the use of crab versus sideslip techniques to maintain lateral tracking under crosswind conditions, the effects of various methods of vertical axis (glideslope) display, guidance and control, and the benefits of coupling flight director signals directly to the rotorcraft control actuators. The program was performed at the Flight Research Laboratory of the National Aeronautical Establishment (NAE), using the NAE Bell 205 Airborne Simulator and was partially funded by the United States Federal Aviation Administration. Experimental results demonstrated that crab technique approaches were satisfactory for all approach speeds and wind conditions investigated (up to 30-knot crosswinds). A factor not addressed in this study was the visual orientation of the landing pad at breakout to flight with visual references. Sideslipping approaches were also shown to be satisfactory until the steady state lateral acceleration exceeded approximately 0.07 G. While coupling of the collective actuator directly to the flight director provided the best glideslope tracking, evaluations showed that the configuration with a 2-cue (pitch and roll) flight director, using only a raw glideslipe presentation, provided satisfactory handling qualities and was considered by FAA and DOT representatives to be certifiable for IFR flight. Coupling of any single axis of control to the flight director was demonstrated to provide slight workload relief benefits and the collective axis was judged to be the most likely candidate axis for this implementation.

15